Evaluating the 20th Century Reanalysis

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Review Article
The Twentieth Century Reanalysis Project

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Compo et al. 2011, doi:10.1002/qj.776

Special thanks to NCEP/EMC, NCDC, Hadley Centre, ACRE partners

The Twentieth Century Reanalysis Project

Summary: An international collaborative project led by NOAA and CIRES to produce high-quality tropospheric reanalyses for the last 130 years ***using only surface pressure observations (this is not a minus!)***.

The reanalyses provide:

-First-ever estimates of near-surface and tropospheric 6-hourly fields extending back to end of the 19th century;

-Estimates of uncertainties in the basic reanalyses;

-Estimates of uncertainties in derived quantities (storm tracks, etc.)

Higher quality in the Northern Hemisphere than in the Southern Hemisphere.

US Department of Energy INCITE, Office of Science computing awards and NOAA Climate Program Office partnership to produce *1871-2008* and extend to 2010 in 2011.

Compo et al. 2011, doi:10.1002/qj.776

Ensemble Filter Algorithm

(Whitaker and Hamill 2002)

Analysis x^a is a weighted average of the first guess x^b and observation y^o

$$x^a = (I-KH)x^b + Ky^o$$

Algorithm uses an ensemble to produce the weight K that varies with the atmospheric flow and the observation network

y^o is surface pressure from the International Surface Pressure Databank v2,

$\mathbf{H}x^b$ is guess surface pressure

$\mathbf{x}$ is pressure, air temperature, winds, humidity, etc. at all levels and gridpoints.

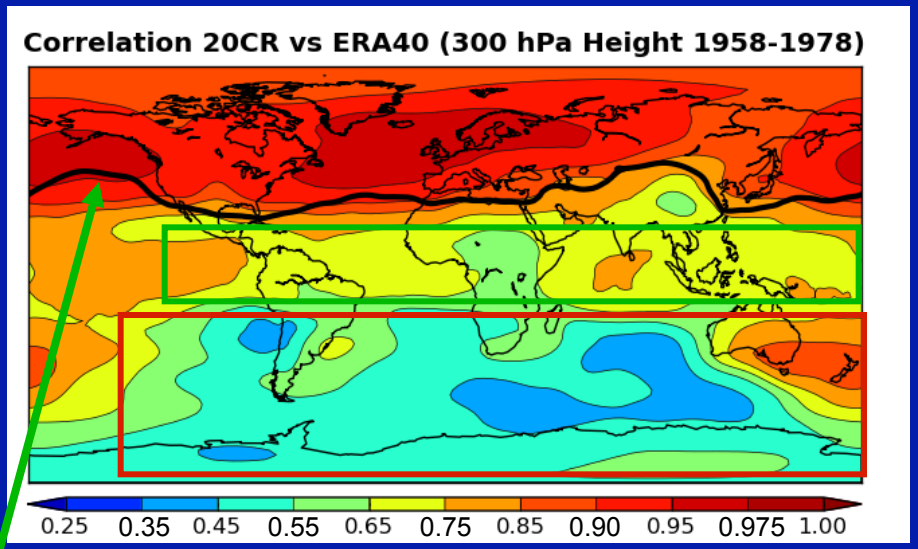
Using 56 member Ensemble

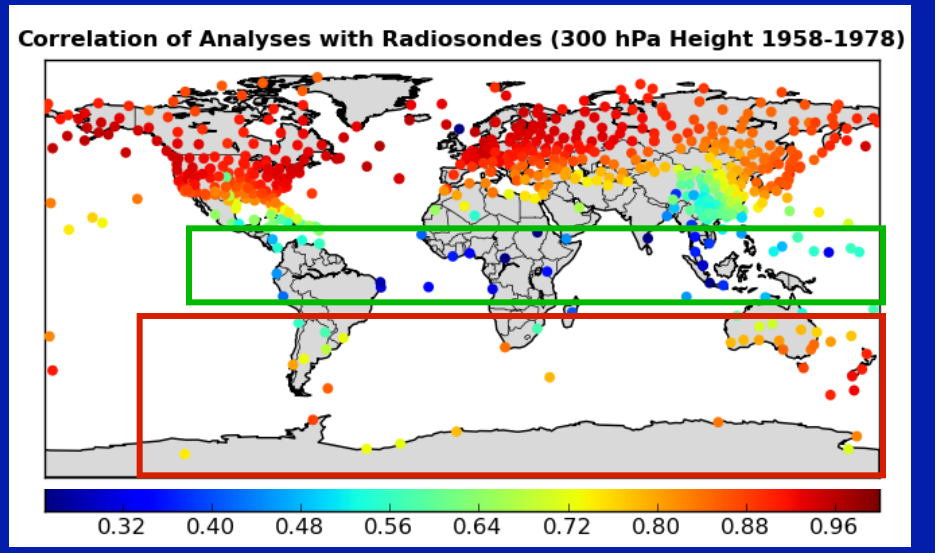
HadISST monthly boundary conditions (*Rayner et al. 2003*)

Version 2 (*1871-2008*): T62, 28 level NCEP GFS08ex model

- time-varying CO_2, solar and volcanic radiative forcing

Local Anomaly Correlation of subdaily 20th Century Reanalysis (20CR), ERA40, and radiosonde **300** hPa geopotential height anomalies (1958 to 1978)





Black curve shows where NCEP-NCAR and ERA40 correlate > 0.975

Northern Hemisphere agreement is excellent where NNR and ERA40 agree.

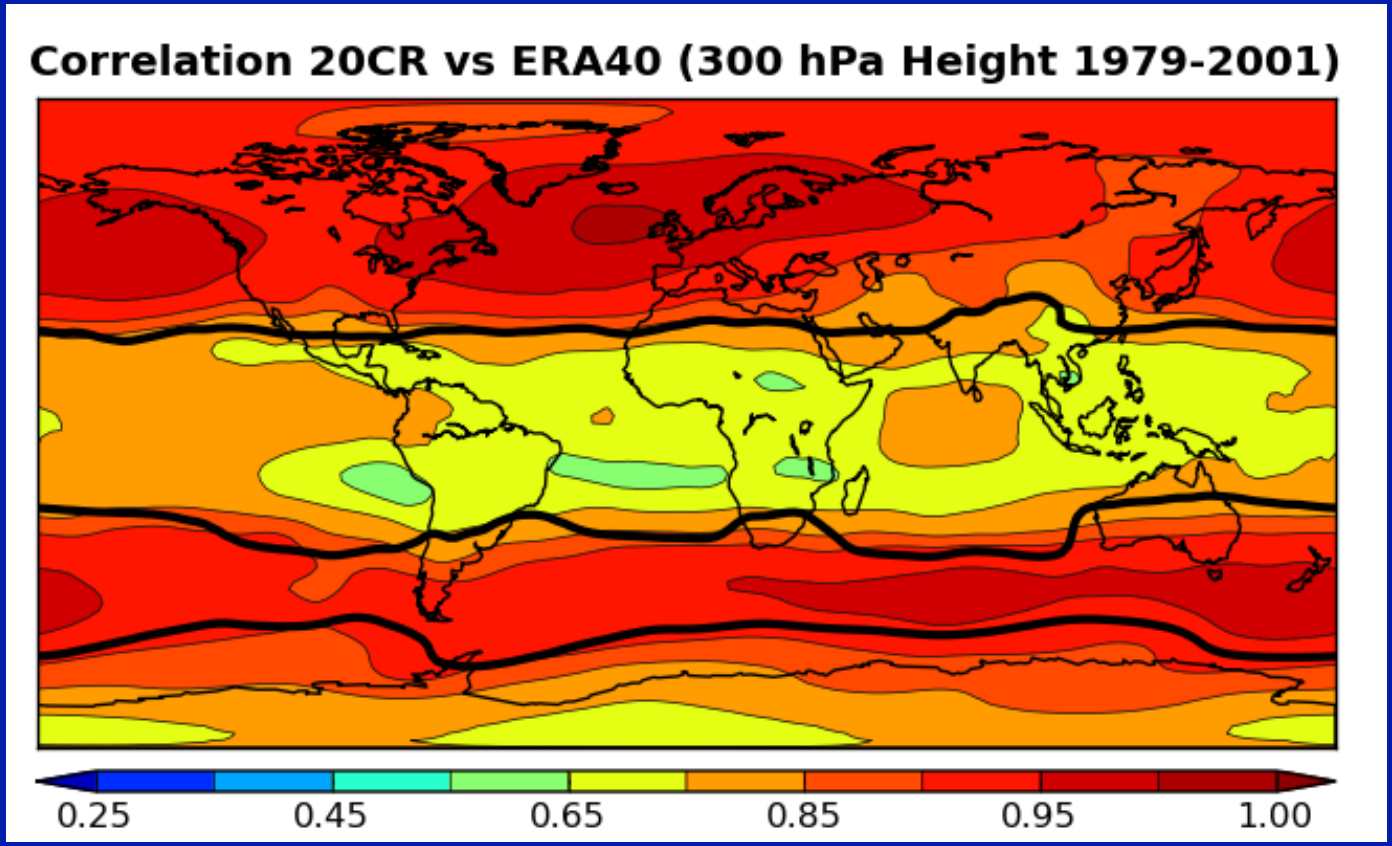
Tropical agreement is moderate to poor with radiosondes but higher with ERA40.

Southern Hemisphere agreement is moderate to poor with ERA40 but higher with radiosondes.

Compo et al. 2011

Local Anomaly Correlation of subdaily 300 hPa geopotential height anomalies from 20th Century Reanalysis (20CRv2) and ERA40 (1979 to 2001)

Black curves show where NCEP-NCAR and ERA40 correlate > 0.975



Northern and Southern Hemisphere agreement are excellent between 20CRv2 and ERA40 when ERA40 has satellite observations.

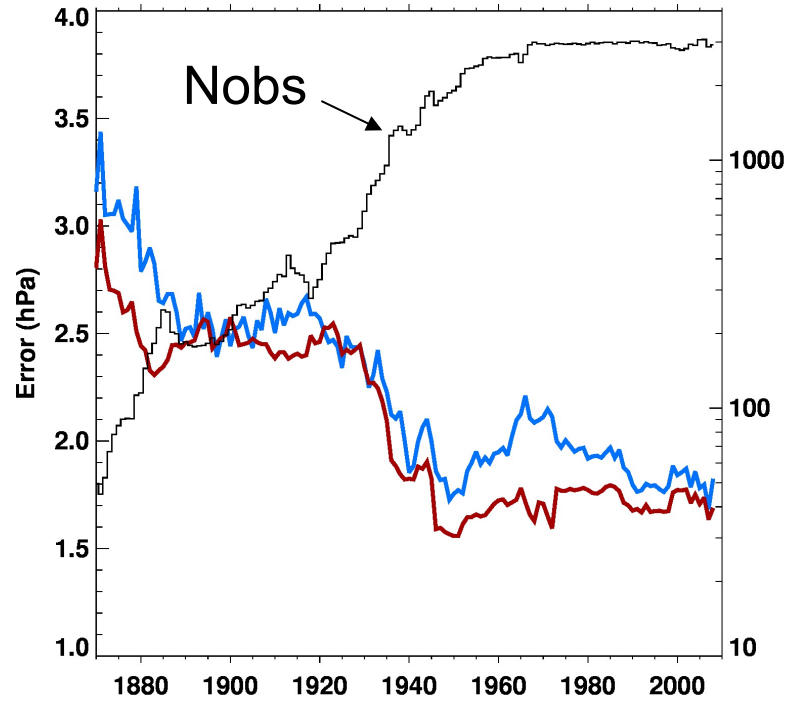
Compo et al. 2011

Surface Pressure uncertainty estimate poleward of 20(S,N)

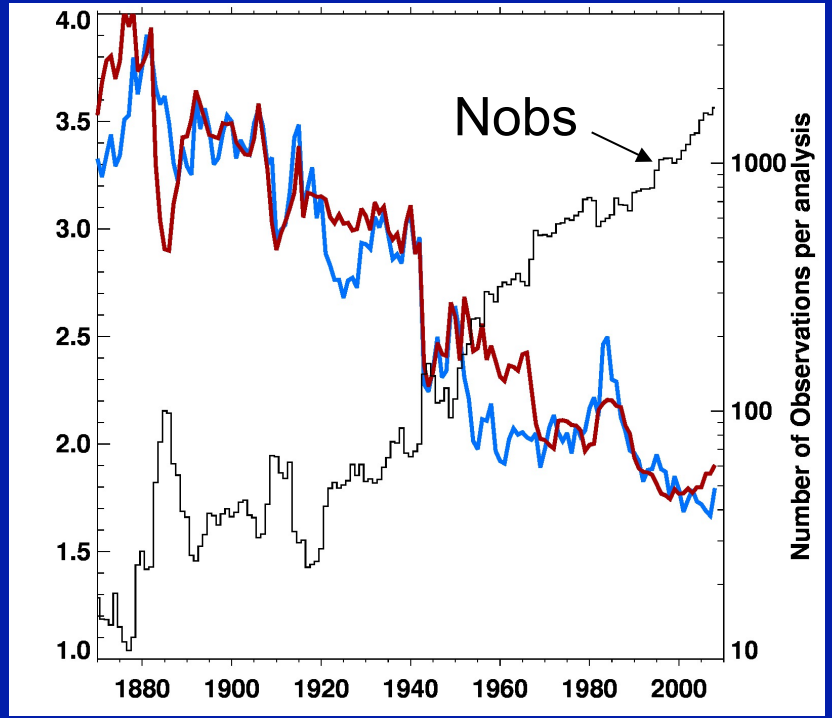
blue actual RMS difference

red expected RMS difference

Northern Hemisphere



Southern Hemisphere

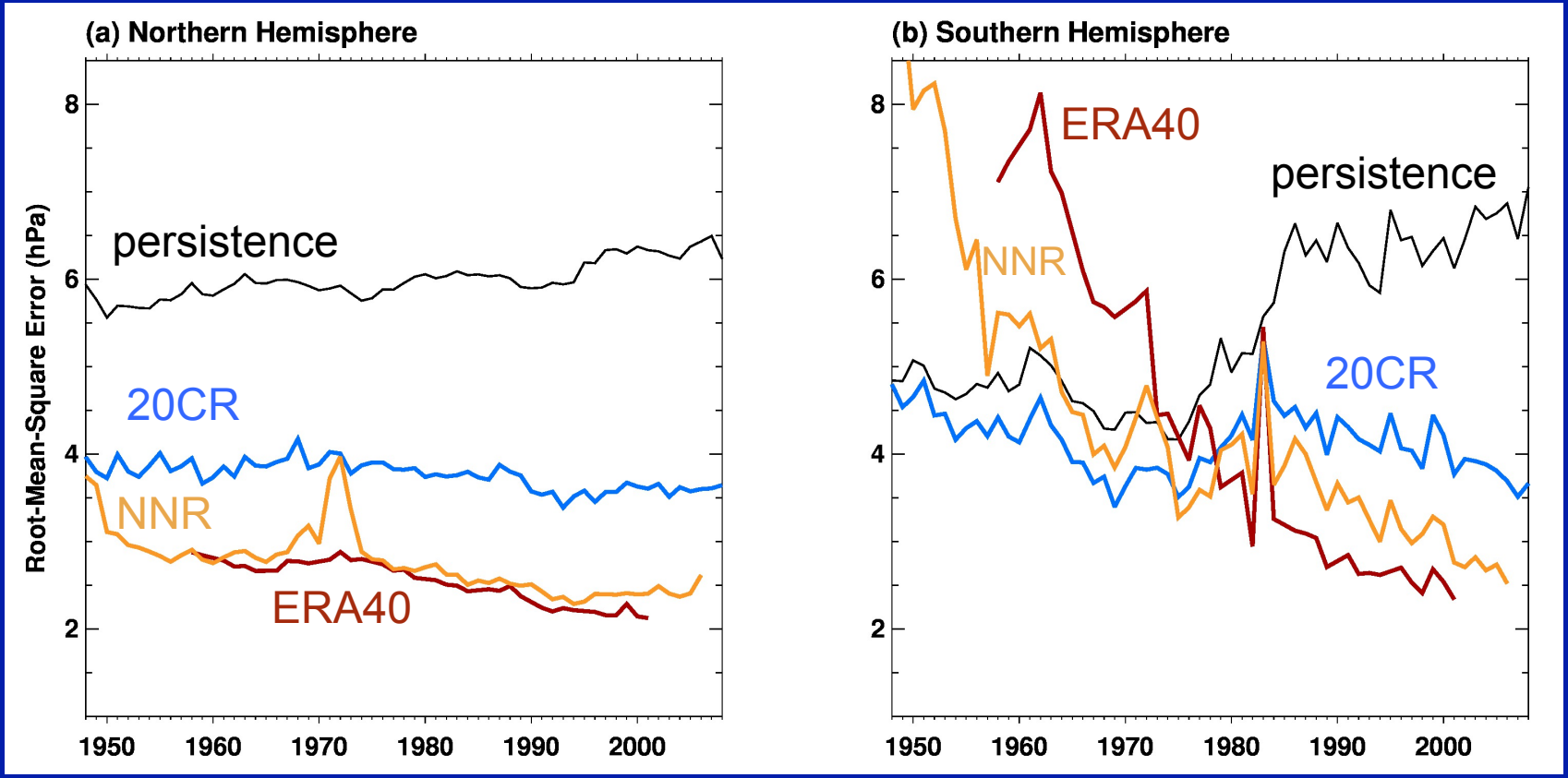


Uncertainty estimates are consistent with actual differences between first guess and pressure observations even as the network changes over more than 100 years!

Compo et al. 2011

RMS Errors of 24 hour forecasts verified against Marine obs

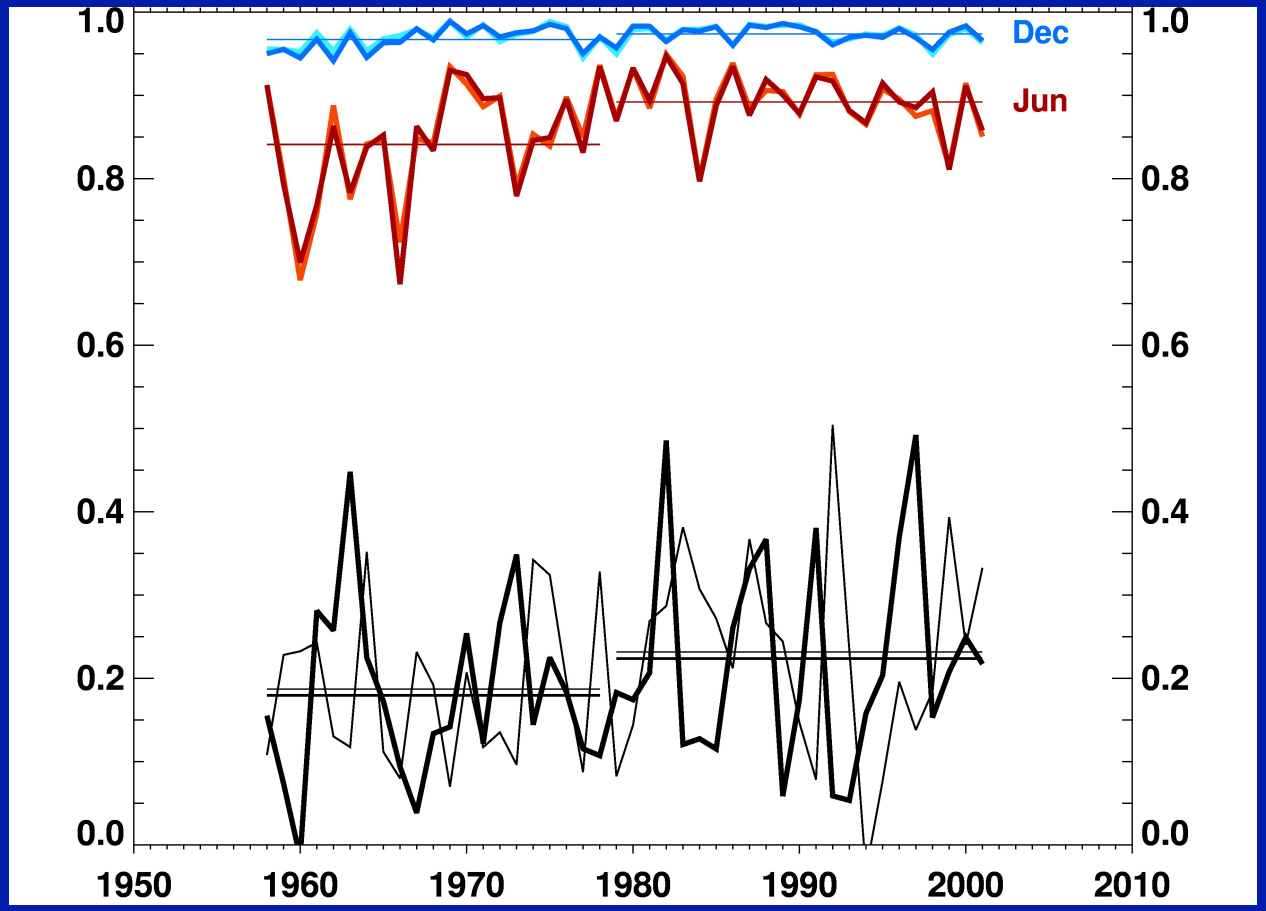
for forecasts initialized with NCEP-NCAR Reanalysis, 20CR, and ERA40 (1948-2008)



Before the satellite era (1970s), there is ***substantially better skill*** for 20CR than for NCEP-NCAR Reanalysis or ERA40 in the Southern Hemisphere despite the lack of upper-air observations.

Compo et al. 2011

Pattern correlation between 20CR and ERA40 and NCEP-NCAR Reanalyses of monthly anomalies of 300 hPa geopotential height



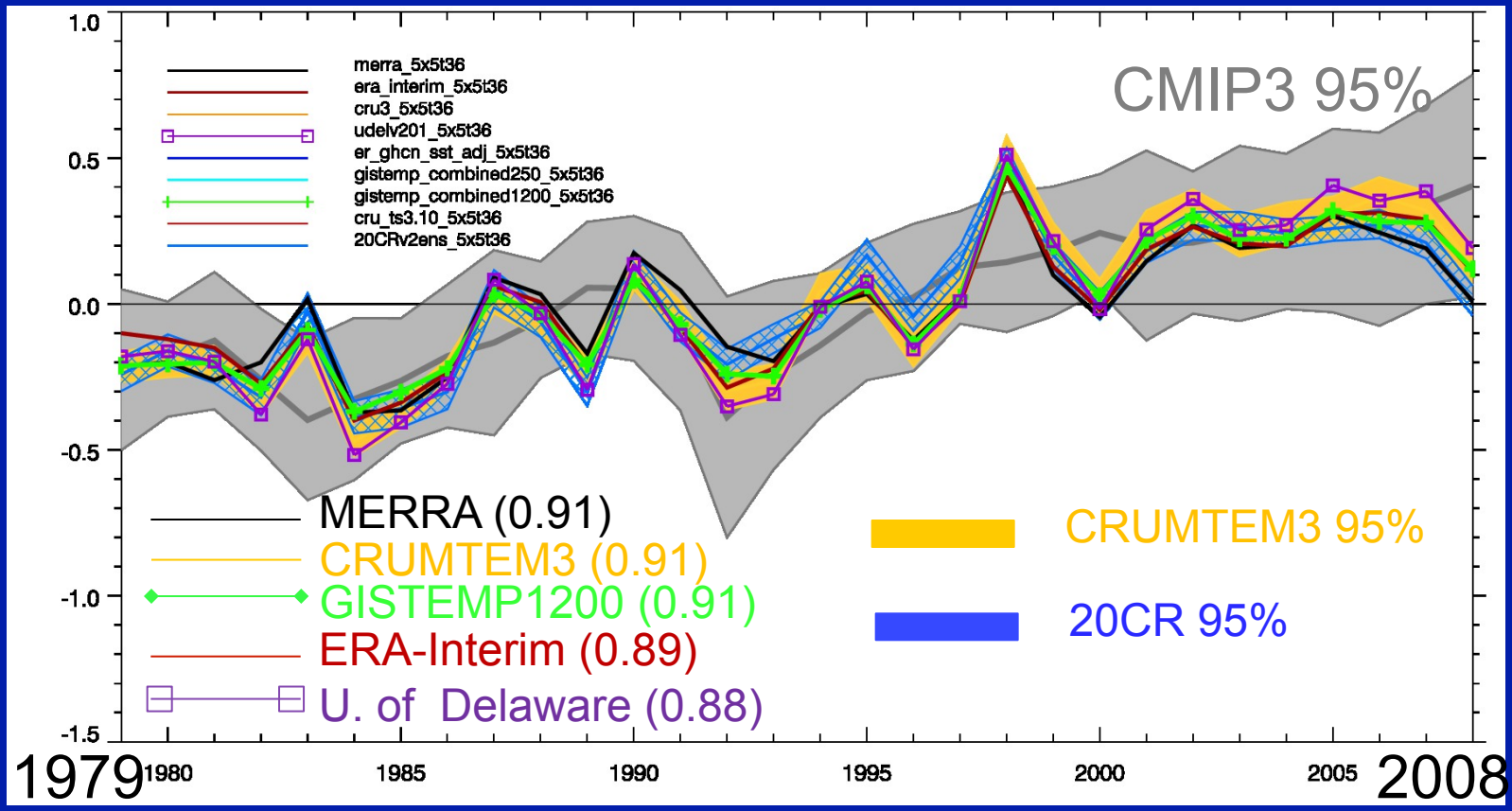
Correlation Between NNR and 20CR (and ERA-40 and 20CR)

Correlation Between NNR and an SST-forced simulation

Reanalysis correlations are much higher than for SST-forced simulation.
1970s change in correlations show satellite data improving NNR and ERA-40.

Compo et al. 2011

1979 to 2008 Near Surface Annual Mean Temperature Anomalies for Land only (50N to 50S)



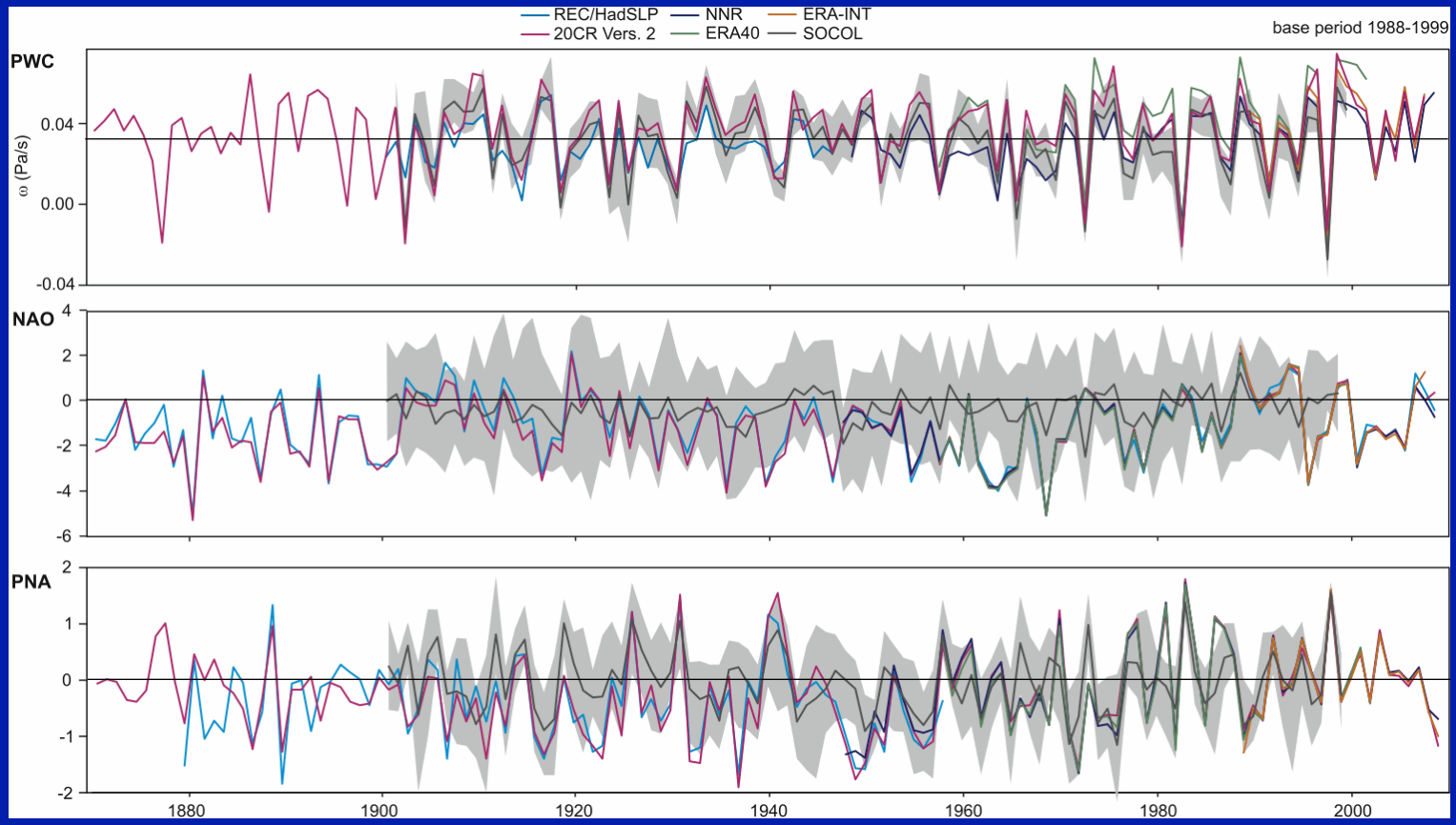
Correlations between 20CR and thermometer-based estimates (in parentheses) are relatively high. 95% error ranges are largely consistent.

Seasonal climate indices from Statistical Reconstructions, SST-forced GCM integrations, and 20th Century, ERA-40, NCEP-NCAR, ERA-Interim Reanalyses.

Pacific Walker Circulation (500 hPa vertical velocity, SONDJ)

North Atlantic Oscillation (Sea Level Pressure, DJF)

Pacific-North America Pattern Index (500 hPa geopotential height, DJF)



1870 2008

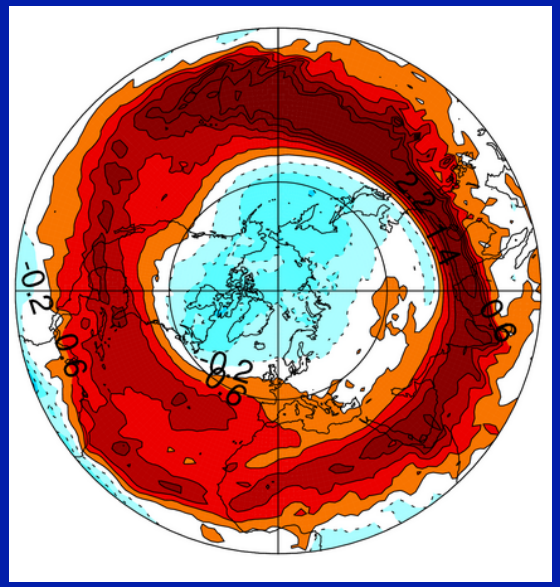
-Agreement is high between observation-based estimates (correlations between ERA-40 and 20CRv2 > 0.95)

-No significant trends from 1870 to 2008 in any of these indices.

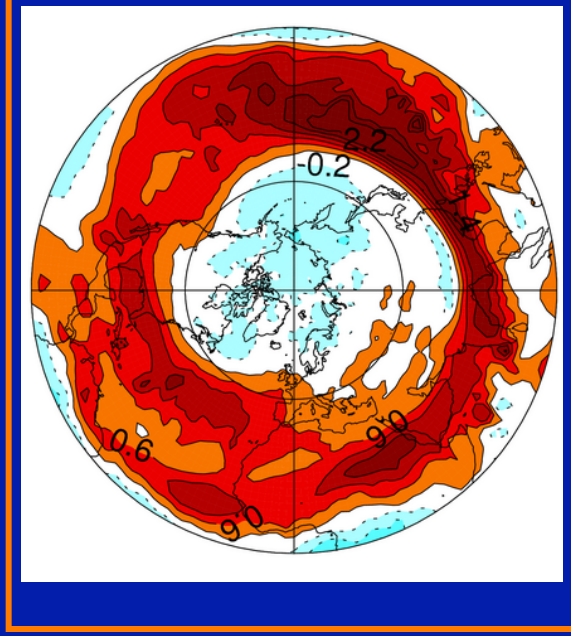
Compo et al. 2011

Storm Track

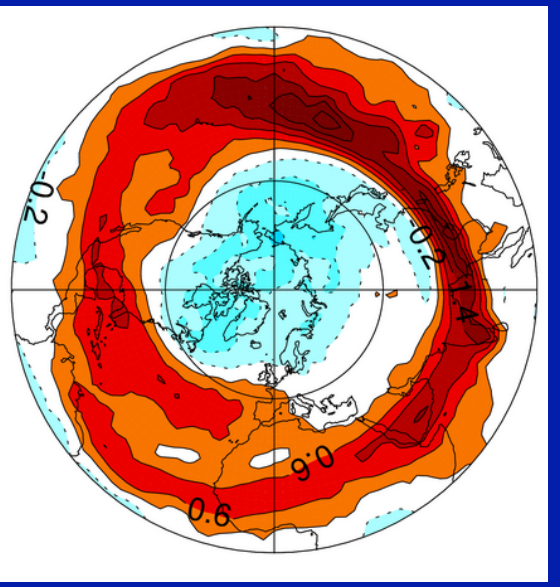
Skewness of Northern Hemisphere 250 hPa *daily* Vorticity (Dec-Feb) 1989/90-2005/06



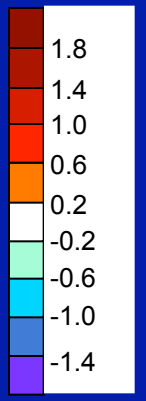
ERA Interim (~50km)
Uses satellite and upper-air data



20CRv2 (~200km)
Surface pressure only

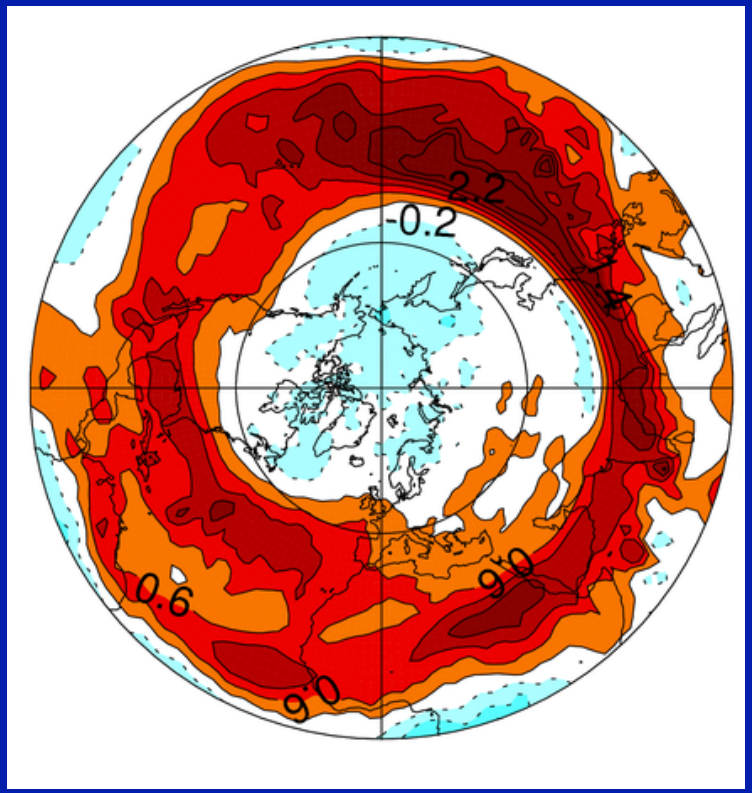


NCEP-NCAR (~200km)
Uses satellite and upper-air data

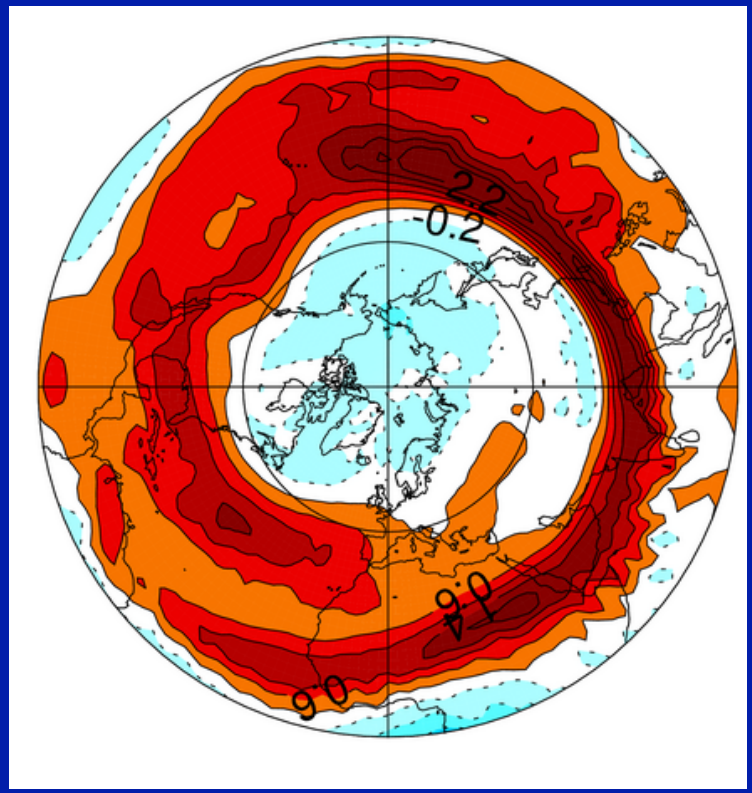


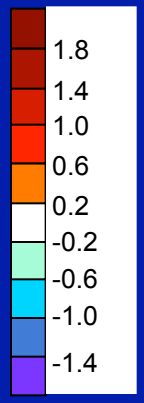
Skewness of 250 hPa Vorticity from 20th Century Reanalyses

DJF 1989/90-2005/06



DJF ***1891/92***-2005/06





Storm Track Features are remarkably robust

Sardeshmukh, Compo, Penland (2012)

Summary

- **Demonstrated that surface-based reanalyses *throughout the troposphere* are feasible using advanced data assimilation and surface pressure observations.**
- **Effectively doubling the reanalysis record length from ~60 year to more than 140 years, allowing current atmospheric circulation patterns to be placed in a broader historical context.** ☺
- **Southern Hemisphere fields may be an improvement over first-generation upper-air based reanalyses before the satellite era.**
- **Challenges: Validating the dataset in regions of sparse observations and rapid change, e.g., the Arctic.**
- **Large-scale variability appears comparable to other reanalyses that used the complete set of meteorological observations.**
- For status updates, email
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  - compo@colorado.edu

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- **Scott D. Woodruff**, NOAA Earth System Research Laboratory, Physical Sciences Division
- **Steven J. Worley**, National Center for Atmospheric Research

Thank you to 59 organizations contributing observations to ISPD:

All Russia Research Institute of Hydrometeorological Information WDC
Atmospheric Circulation Reconstructions over the Earth (ACRE)
Australian Bureau of Meteorology
Australian Meteorological Association, Todd Project Team
British Antarctic Survey
Cook Islands Met Service
Danish Meteorological Institute
Deutscher Wetterdienst
EMULATE
Environment Canada
ETH-Zurich
European Reanalysis and Observations for Monitoring
GCOS AOPC/OOPC WG on Surface Pressure
GCOS/WCRP Working Group on Datasets
Hong Kong Observatory
IBTRACS
Icelandic Meteorological Office
ICOADS
Instituto Geofisico da Universidade do Porto
IEDRO
JAMSTEC
Japan Meteorological Agency
Jersey Met Dept.
KNMI
MeteoFrance
MeteoFrance – Division of Climate
Meteorological and Hydrological Service, Croatia
National Center for Atmospheric Research
Nicolaus Copernicus University
Niue Met Service
NIWA
NOAA Climate Database Modernization Program
NOAA Earth System Research Laboratory
NOAA National Climatic Data Center
NOAA National Centers for Environmental Prediction
NOAA Northeast Regional Climate Center at Cornell U.
NOAA Midwest Regional Climate Center at UIUC
NOAA Pacific Marine Environmental Laboratory
Norwegian Meteorological Institute
Oldweather.org
Ohio State U. – Byrd Polar Research Center
Portuguese Meteorological Institute (IM)
Proudman Oceanographic Laboratory
SIGN - Signatures of environmental change in the observations of the Geophysical Institutes
South African Weather Service
Univ. of Bern, Switzerland
UK Met Office Hadley Centre
U. of Colorado-CIRES/Climate Diagnostics Center
U. of East Anglia-Climatic Research Unit
U. of Giessen –Dept. of Geography
U. of Lisbon-Instituto Geofisico do Infante D. Luiz
U. of Milan-Dept. of Physics
U. Rovira i Virgili-CCRG
U. of South Carolina
U. of Toronto-Dept of Physics
U. of Washington
World Meteorological Organization - MEDARE
ZAMG (Austrian Weather Service)

International Surface Pressure Databank version 2 (ISPD)

Subdaily observations assembled in partnership with

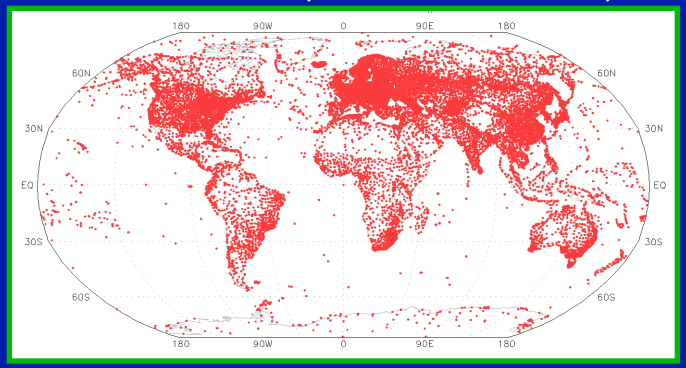
GCOS AOPC/OOPC Working Group on Surface Pressure

GCOS/WCRP Working Group on Observational Data Sets for Reanalysis

Atmospheric Circulation Reconstructions over the Earth (ACRE)

Land data Component: merged by NOAA NCDC, NOAA ESRL, and CU/CIRES

- **33 data sources**
- **33,653 stations**
- **1.7 billion obs**
- **1768-2008**



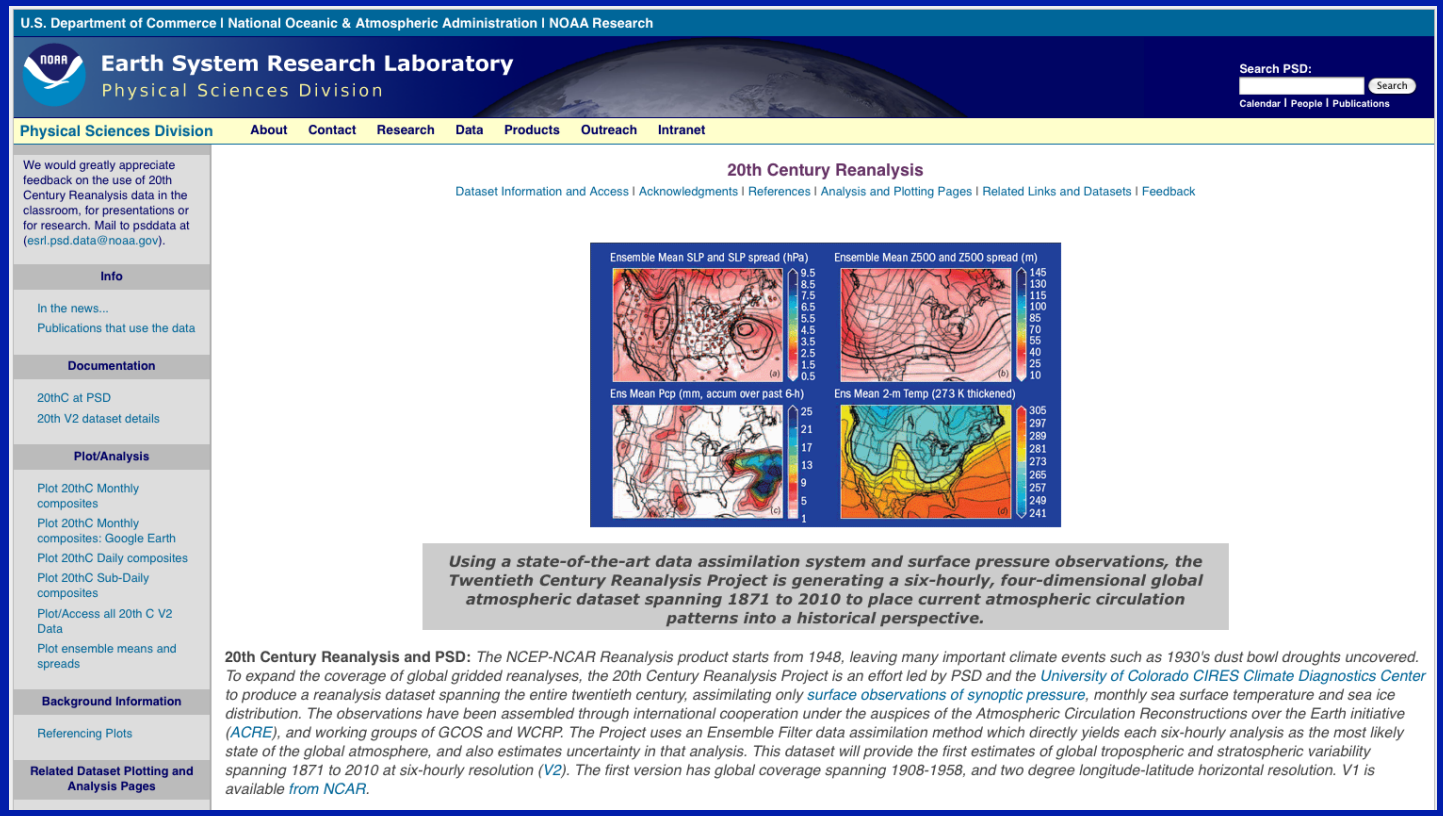
Marine data component: **ICOADS** merged by NOAA ESRL and NCAR NOAA

Tropical Cyclone Best Track data component: **IBTrACS** merged by NOAA NCDC

See Poster T176A by C. McColl et al.

Extra Slides

www.esrl.noaa.gov/psd/data/20thC_Rean/



20CR homepage has links for publications that use the data, data access and tools for visualizing and analyzing the data.

Historical Reanalysis Status and Plans

20th Century Reanalysis Project http://www.esrl.noaa.gov/psd/data/20thC_Rean

- Data Access: Analyses and ISPD (with feedback) freely available from NCAR, analyses from NOAA/ESRL and DOE NERSC. Coming Soon: NOAA/NCDC.
- **Fall 2011**: 1871-2008, expand to 2010 (includes time-varying CO2, volcanic aerosols, GFS from NCEP). **Ensemble mean and spread and some individual member variables online now**.
  - http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html (NOAA ESRL)
  - http://dss.ucar.edu/datasets/ds131.1 (NCAR)
  - http://portal.nersc.gov/20C_Reanalysis **Every member** (US Dept of Energy, NERSC)
  - http://nomads.ncdc.noaa.gov (NOAA NCDC, coming soon)
  - Coordinate with PCMDI CMIP5 distribution and validation for IPCC AR5

ECMWF Reanalysis Archive-Climate (ERA-CLIM)

- Series of reanalyses, including Surface-observation based back to 1900 (ERA-20C).
- ERA-20C: T159 spectral (~125km grid spacing)
- ERA-20C: **Available 2012**

Project Status and Plans (con't)

Sparse Input Reanalysis for Climate Applications (SIRCA)

SIRCA 1850-2014

- Higher resolution (T126 ~100km or higher)
- improved methods (e.g., improved quality control, bias correction)
- More input data (e.g., ACRE)
- latest model from NCEP
- Include uncertainty in forcings (e.g., ensemble of SSTs and Sea Ice, CO2, solar)
- Release Date Uncertain

Ocean Atmosphere Reanalysis for Climate Applications

OARCA 1800?-2017

- Higher resolution (T382 or higher)
- improved methods (e.g., include coupled Cryosphere-Ocean-Land-Atmosphere-Chemistry system, link with SODA advances, possibly NOAA CarbonTracker advances)
- More input data (e.g., ACRE-facilitated, maybe winds and T, storm position, trace gases)
- latest model from NCEP, multi-model with other models (e.g., NASA, NCAR, GFDL, ESRL)
- Release Date Uncertain

Advances and Improvements towards

Sparse Input Reanalysis for Climate Applications (SIRCA)

spanning 19th-21st centuries over the next 2-10 years

1. More land and marine observations back to early 19th century, especially Southern Hemisphere and Arctic.
2. User requirements for, and applications of, reanalyses
3. Higher resolution, improved methods, possibly other surface variables (e.g., wind, T, Tropical Cyclone position)
4. Uncertainty in forcings (e.g, CO2, solar, SST)
5. Possibly Multi-model (e.g., NASA, NCAR, NCEP, GFDL, ESRL)

Available 2014 – SIRCA (*1850-2014*)

Available 2017 – include coupling, OARCA (*1800-2016*)

Requires international cooperation, e.g.,

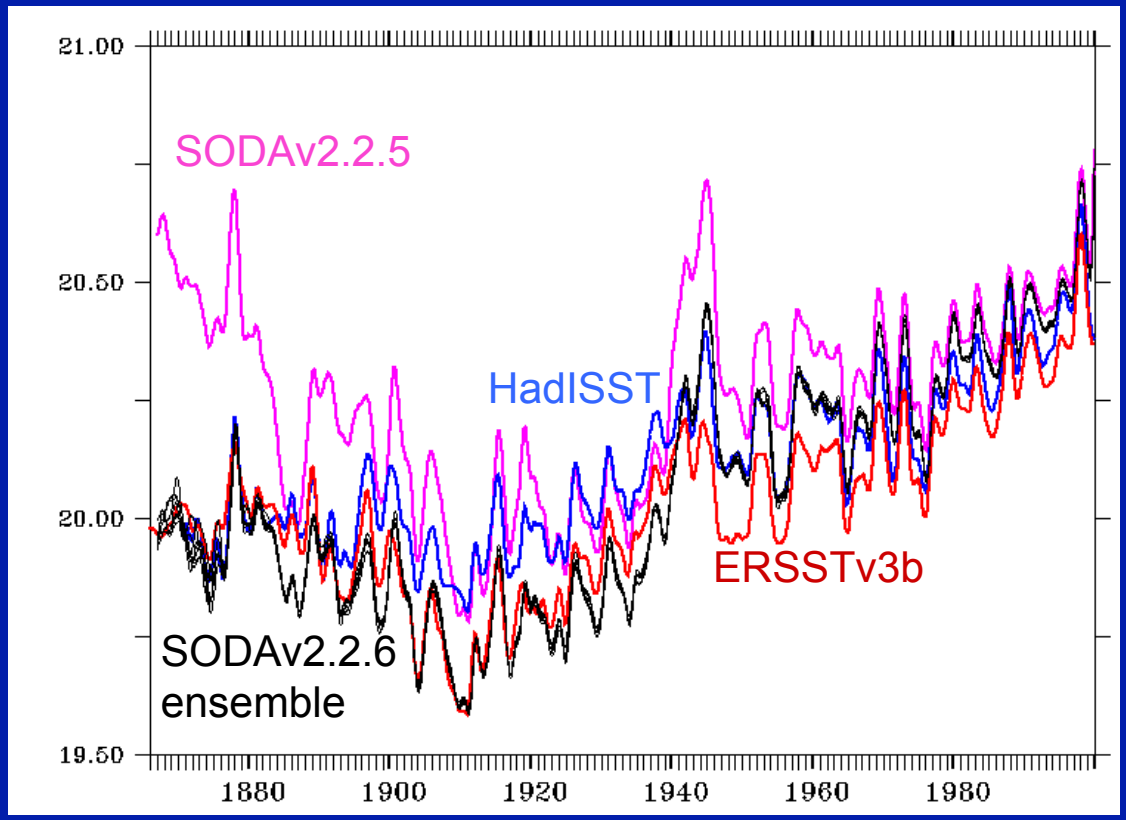
Atmospheric Circulation Reconstruction over the Earth initiative

http://www.met-acre.org

Global Ocean Sea Surface Temperature (60N-60S)

from Simple Ocean Data Assimilation SST *ensemble* (SODAv2.2.6) compared to SST reconstructions (HadISST and NOAA ERSST) and SODAv2.2.5 using only 20CR ensemble mean

In these, SODA assimilates only SST data



1866 1999

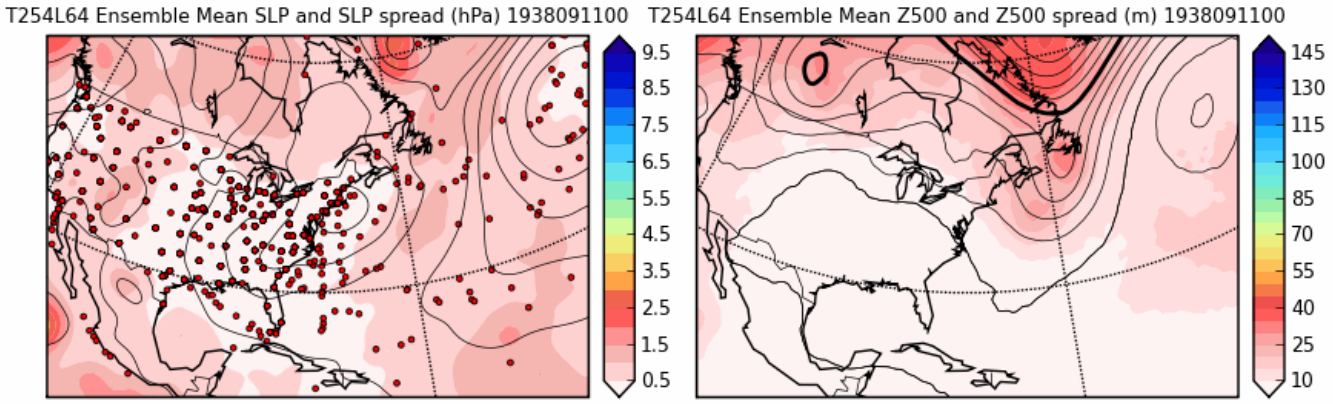
SODAv2.2.5 is too warm early in record because 20CR ensemble-mean wind-stress is too weak.

Surprisingly, SODAv2.2.6 ensemble corresponds better to NOAA ERSSTv3b at times, despite 20CR having HadISST1.1 as boundary condition.

Higher resolution example of Sparse Input Reanalyses for Climate Applications (SIRCA)

2008 NCEP GFS at ~50km resolution

September 1938 New England (movie)



T254L64 (~50 km)

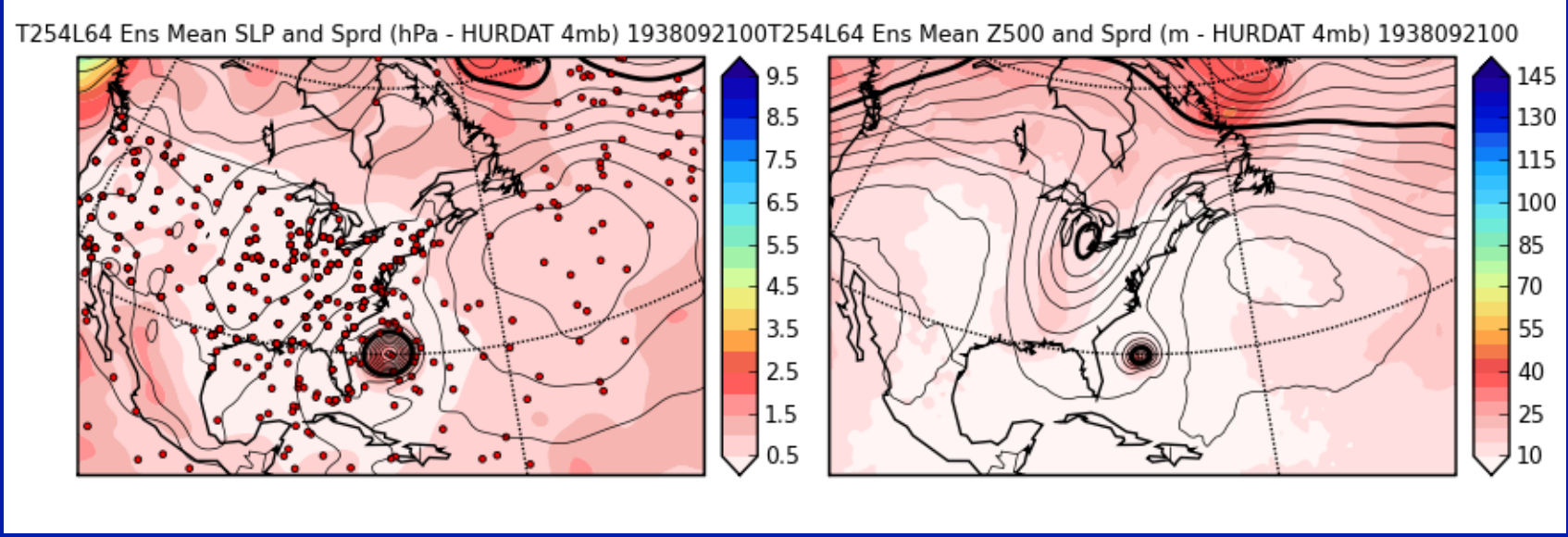
Is the extraordinary upper-level trough correct?

2008 NCEP GFS at ~50km resolution

21 September 1938 00 UTC

Sea Level Pressure

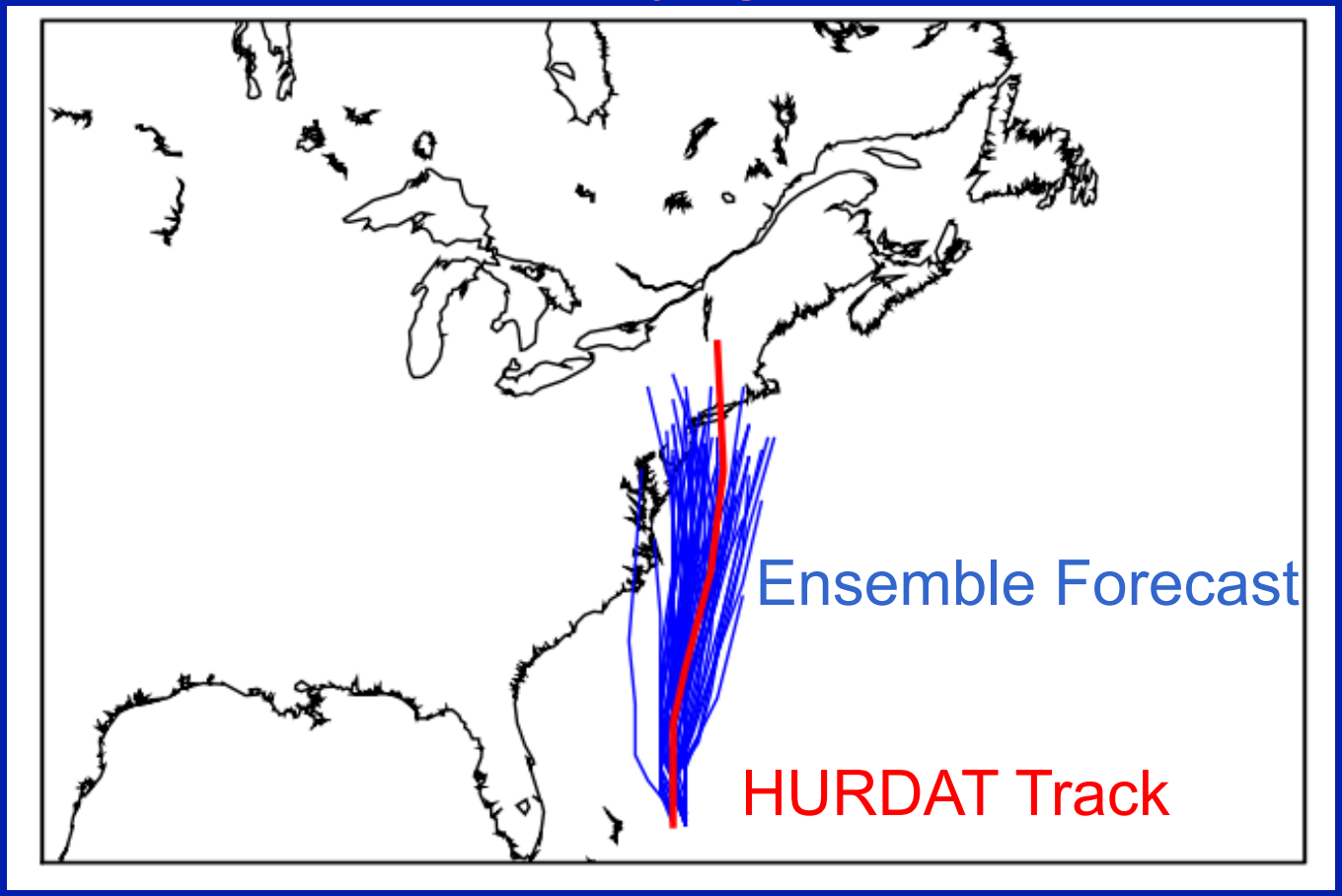
500 hPa geopotential height



Is the extraordinary upper-level trough correct?

Any Skill Forecasting the Track?

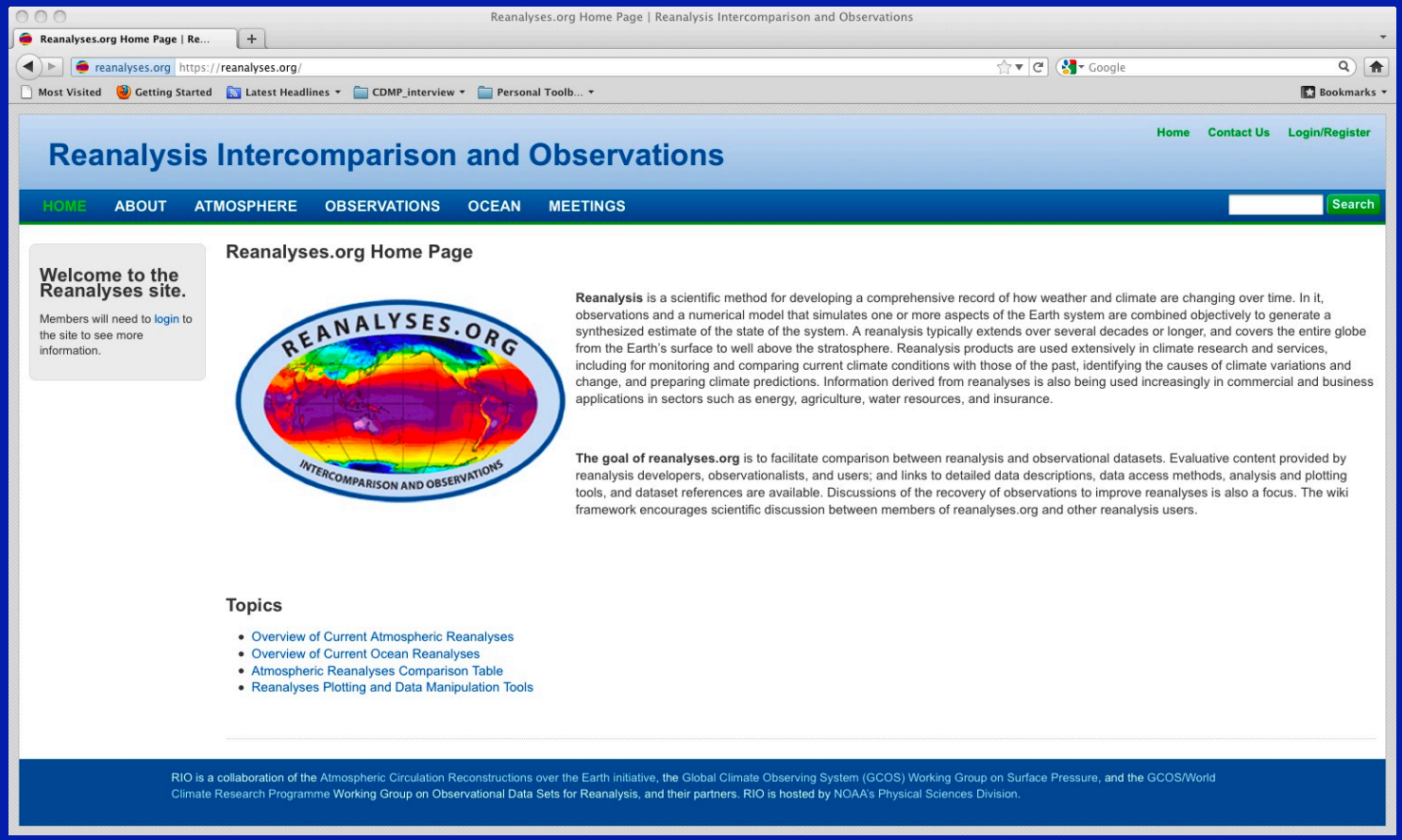
36 hour forecast verifying 21 Sept 1938 18Z



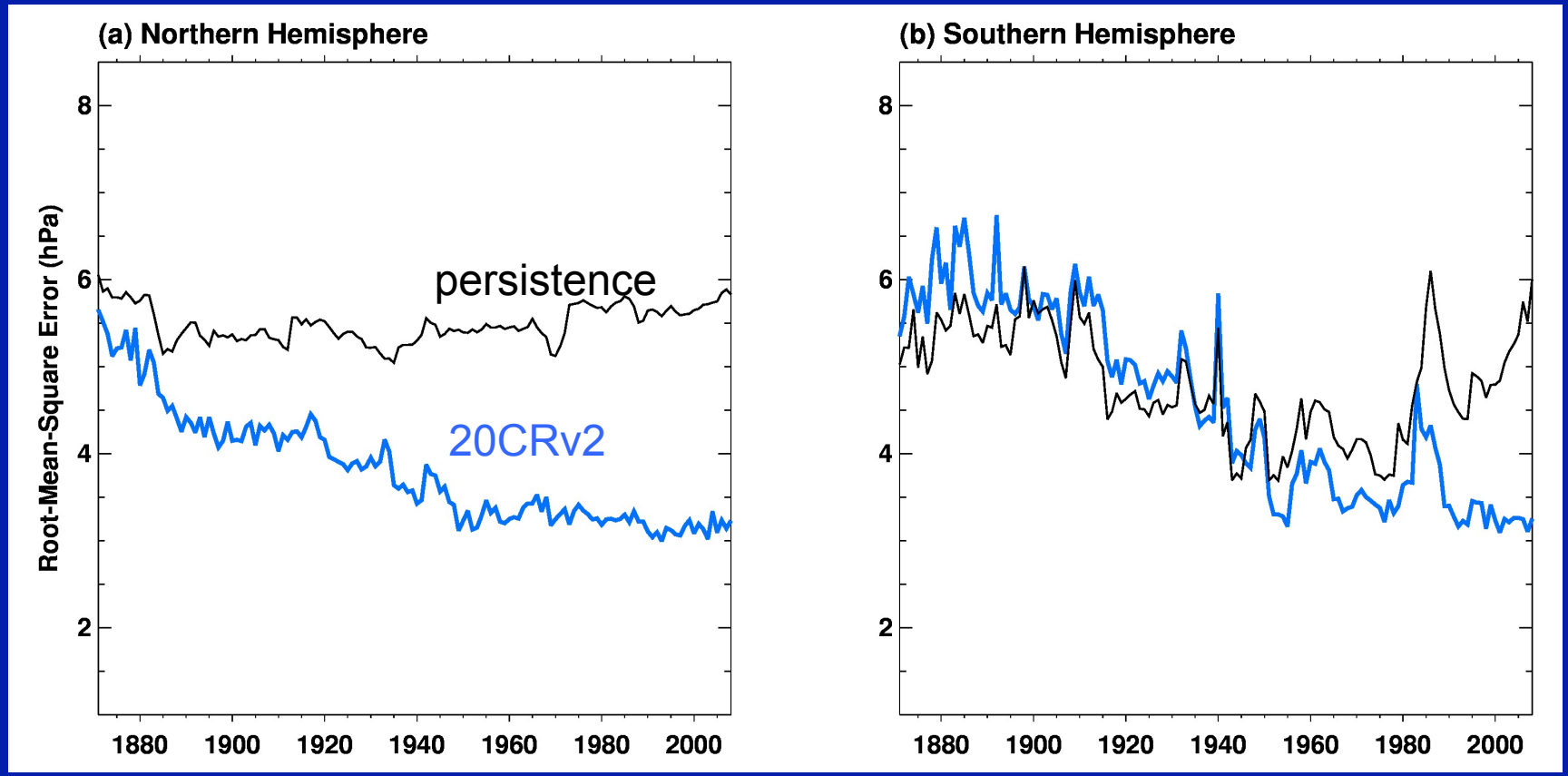
using 56 ensemble members T254L64 (about 0.5 degree)

www.reanalyses.org

Wiki for comparing Reanalyses with each other and with observations



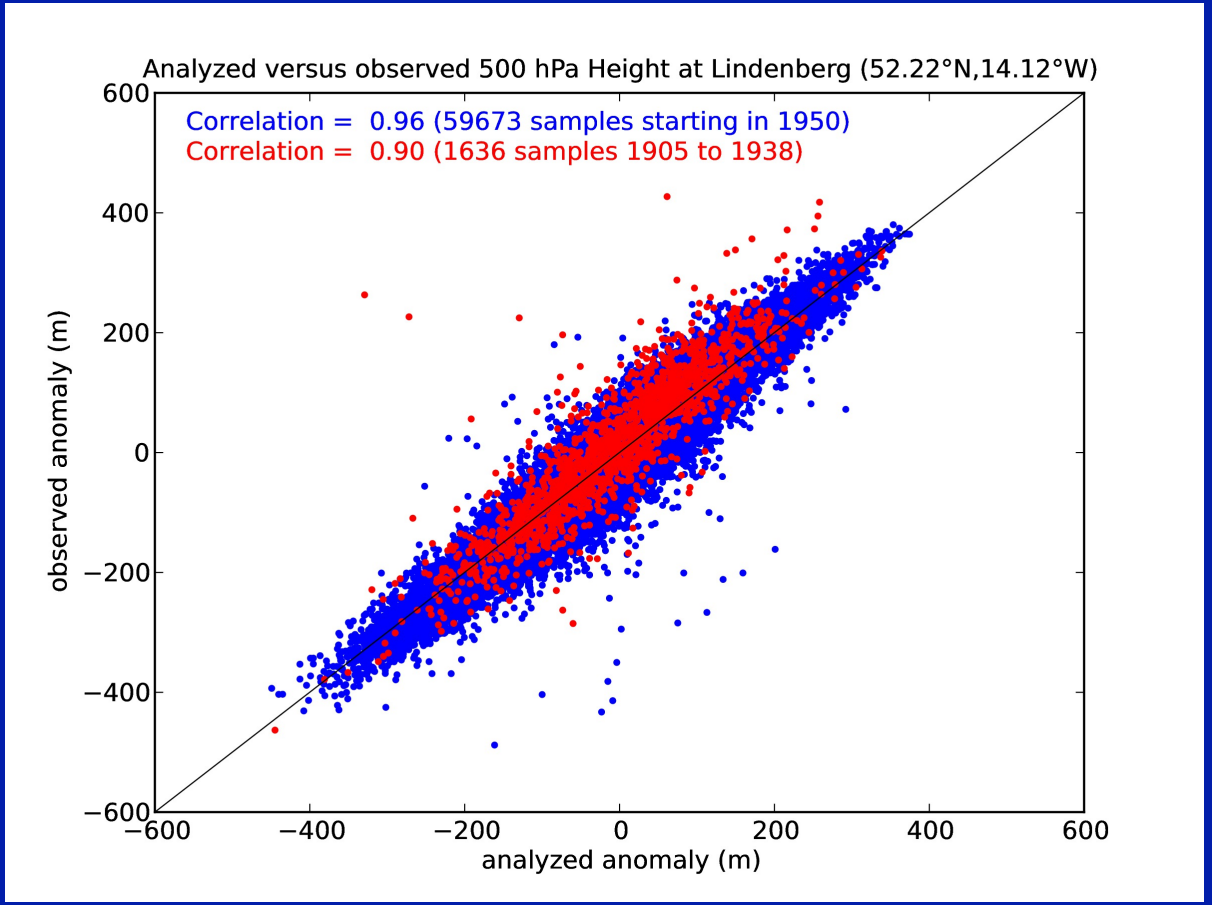
Root Mean Square difference of Surface and Sea Level Pressure Observations and 24 hour Forecasts from 20th Century Reanalysis (1871-2008)



Northern Hemisphere 24 hr forecasts beat persistence even in 1871.
Southern Hemisphere not better until after 1950.

Subdaily 500 hPa Geopotential Height anomalies from observations and 20th Century Reanalysis compare well.

1905-2006 Measurements from kites, aircraft, registering balloon, and radiosondes at Lindenberg, Germany



Observations from CHUAN dataset (*Stickler et al. 2010*)

Local Anomaly Correlation of Twentieth Century Reanalysis and upper-air geopotential height observations from radiosondes and other platforms

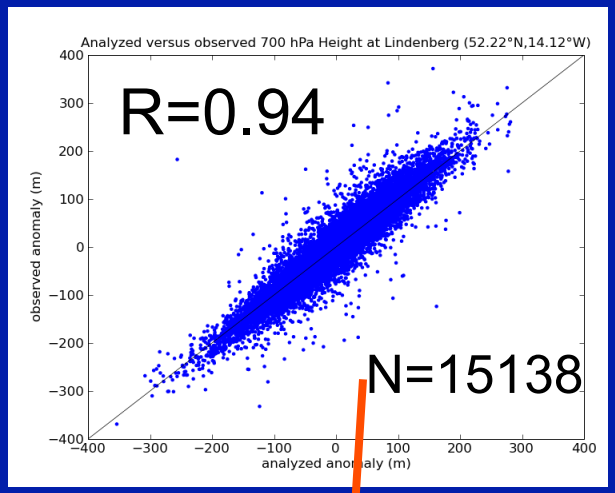
1908-1958 data from kites, aircraft, radiosondes at Lindenberg, Germany

Upper-air observations with at least 730 ascents

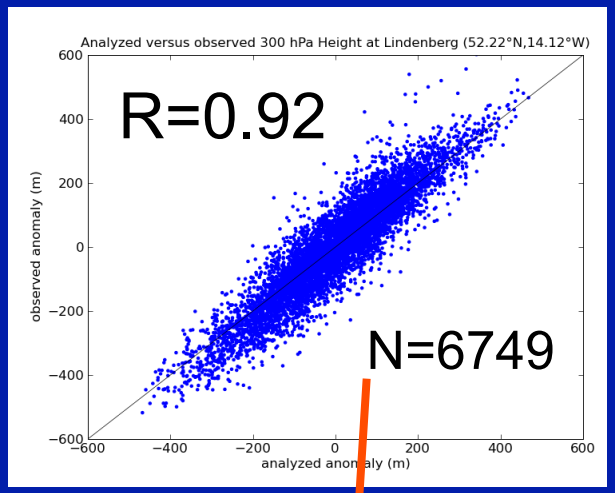
Courtesy

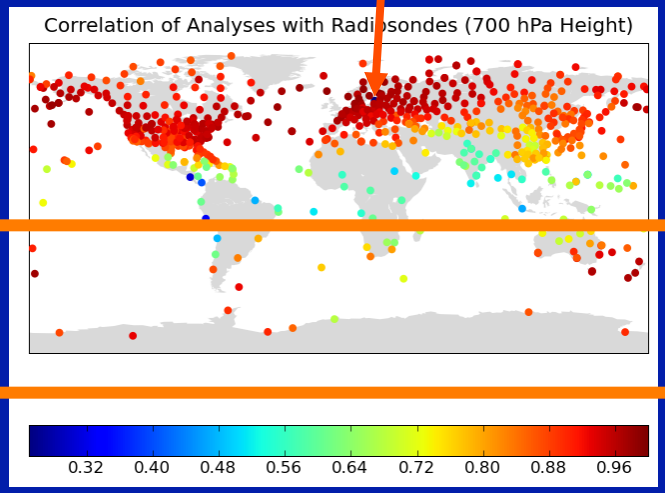
ETH Zurich

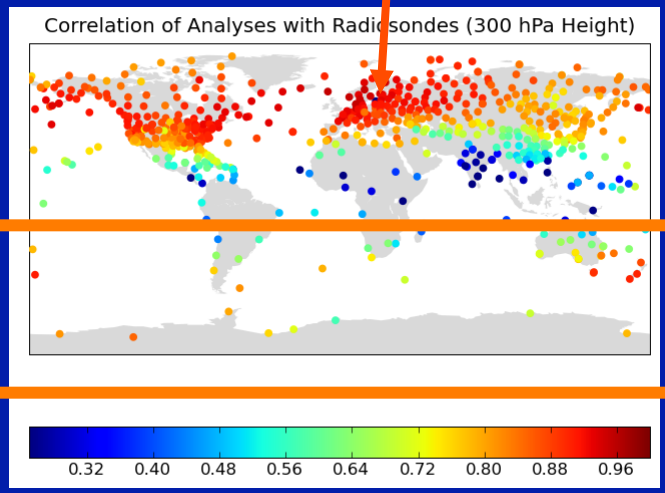
700 hPa



300 hPa







Agreement with Southern Hemisphere extratropics is good.

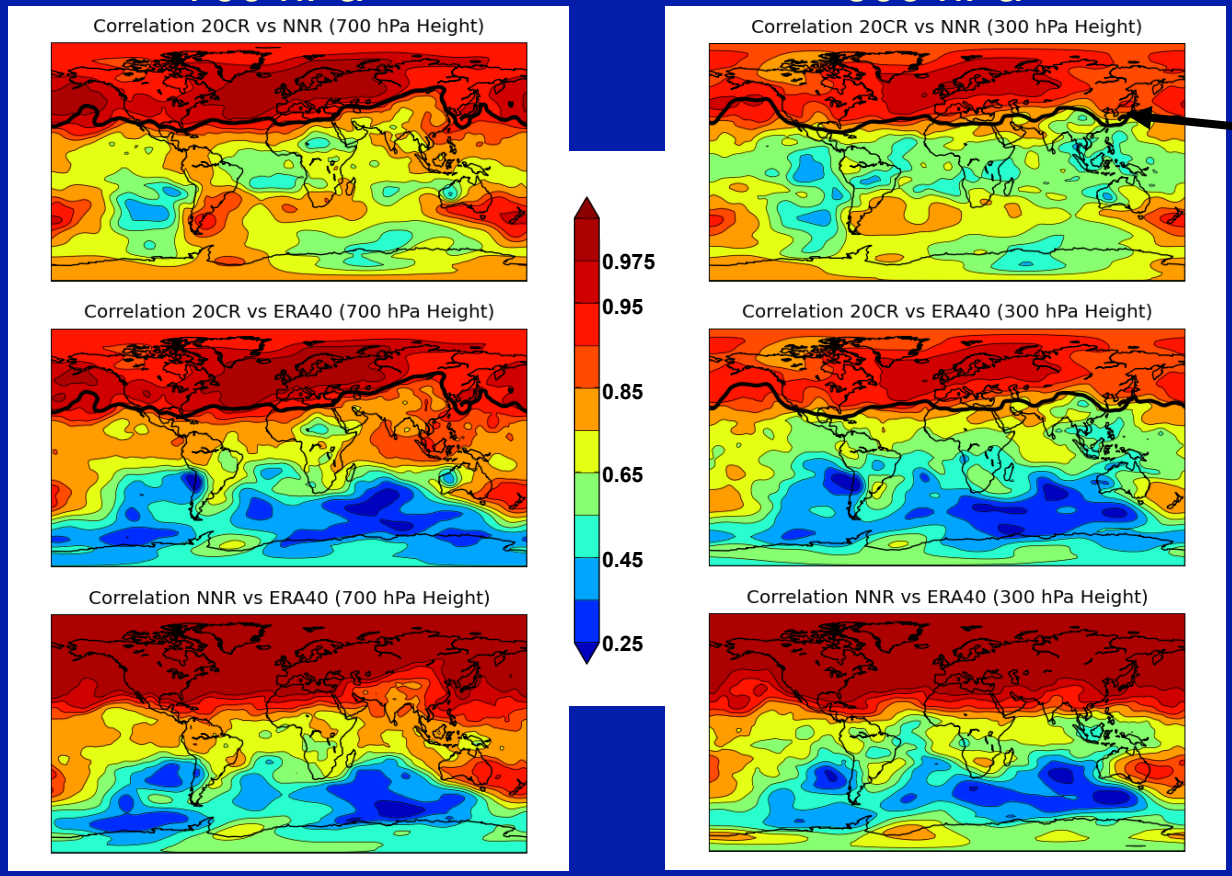
Local Anomaly Correlation of Twentieth Century Reanalysis (20CR), NCEP-NCAR Reanalysis (NNR), and ERA40 twice-daily geopotential height anomalies (1958)

700 hPa | 300 hPa

20CR vs. NNR

20CR vs. ERA40

NNR vs. ERA40



0.975 correlation between NNR and ERA40

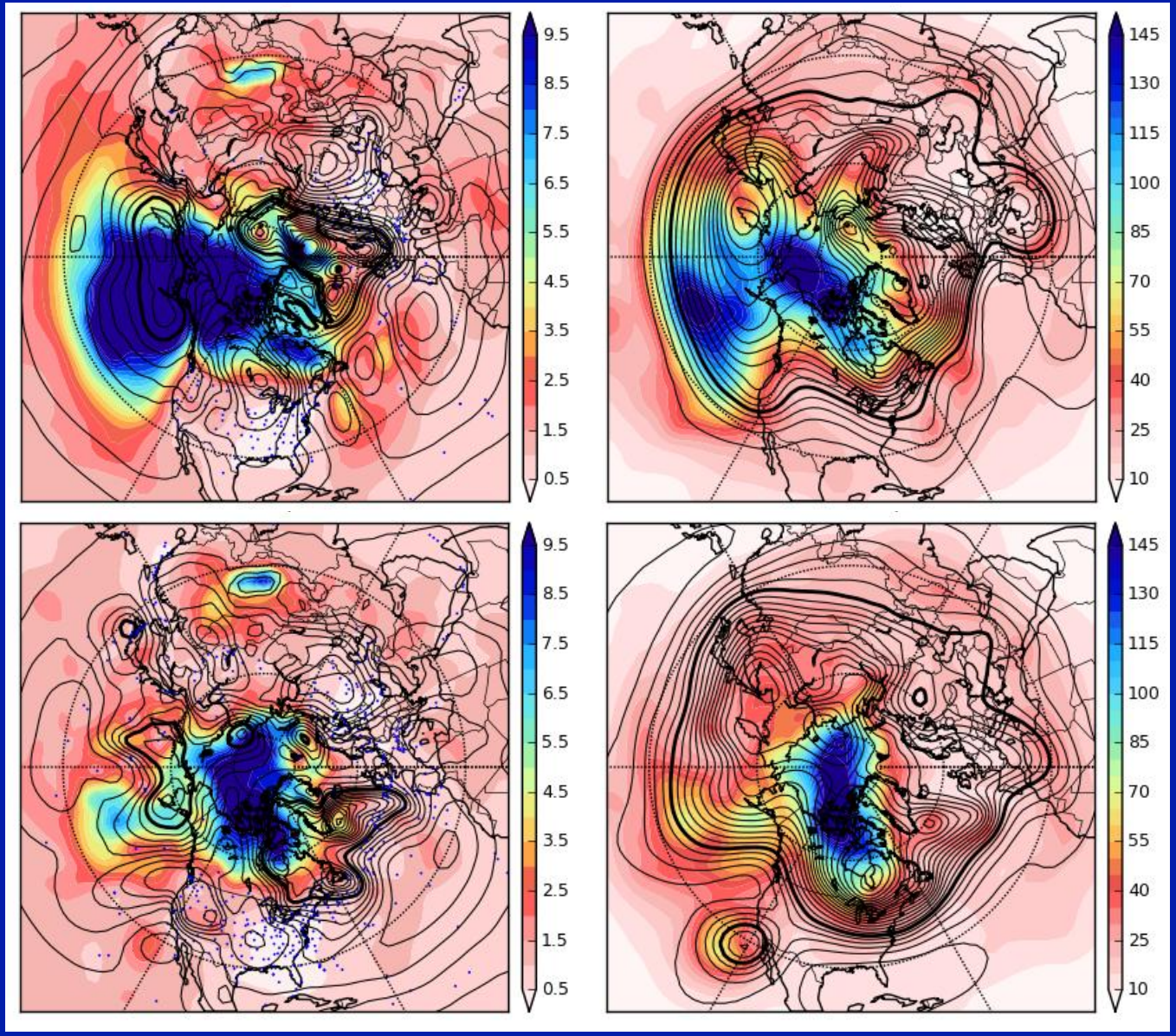
Southern Hemisphere agreement with ERA40 is poor.

Northern Hemisphere agreement is excellent.
Southern Hemisphere agreement is moderate to poor.
Is 20CR useful in Southern Hemisphere?

Analyses for selected dates in 1894 and 1914

1894

1914



Sea Level Pressure

500 hPa Geopotential Height

Contours- ensemble mean

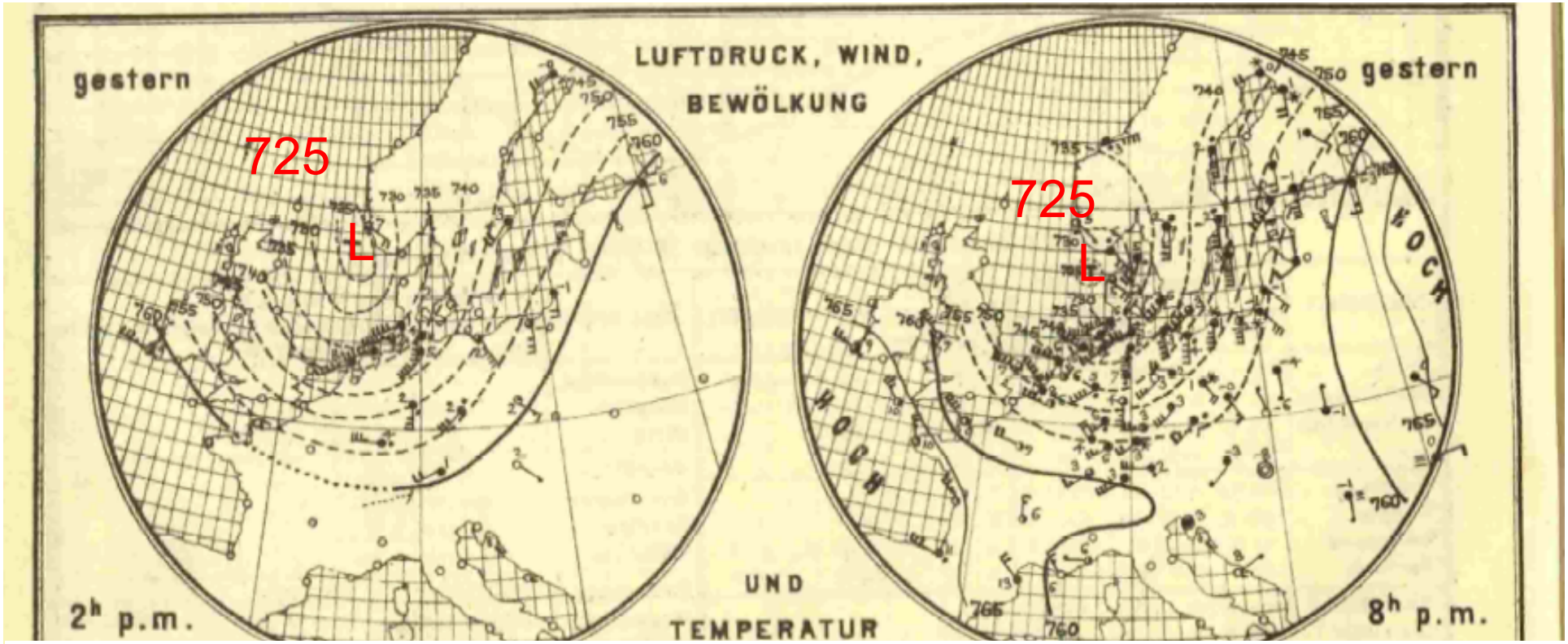
Shading- blue: more uncertain, white: more certain

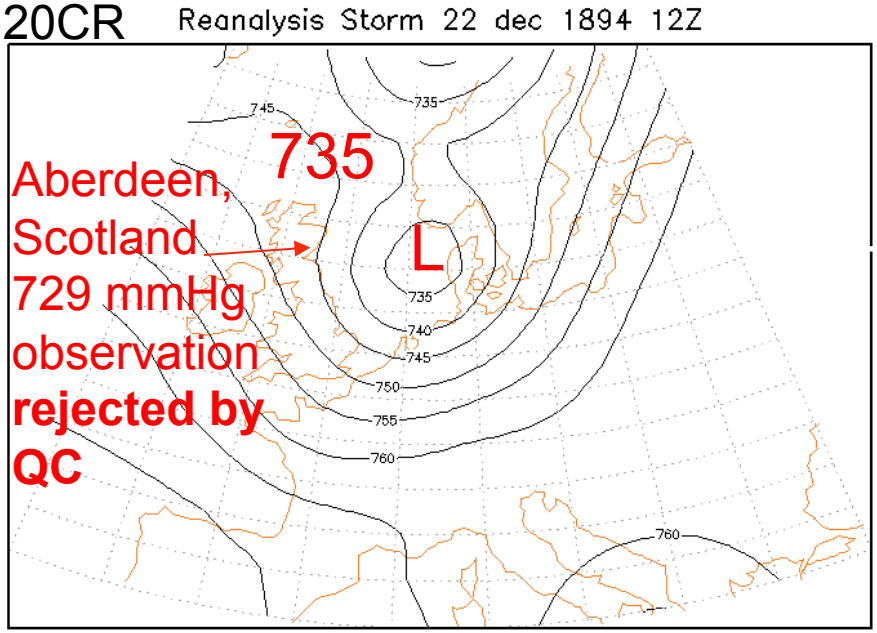
Blue dots: Obs locations

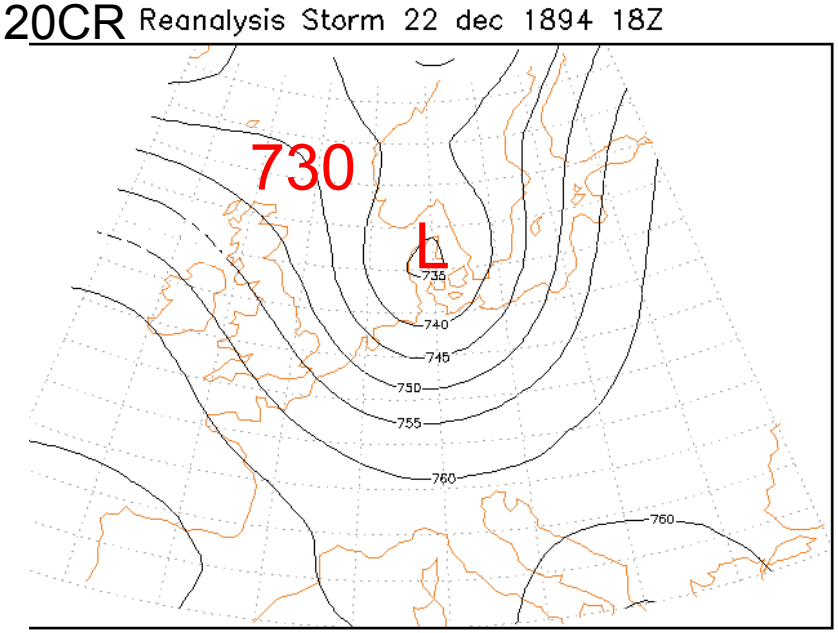
De Storm van 1894 (Zenit. 2010)

Henk de Bruin and Huug van den Dool

Frank Beyrich and **Britta Bolzmann** (DWD)
provided 1894 weather maps of the
Seewarte Hamburg



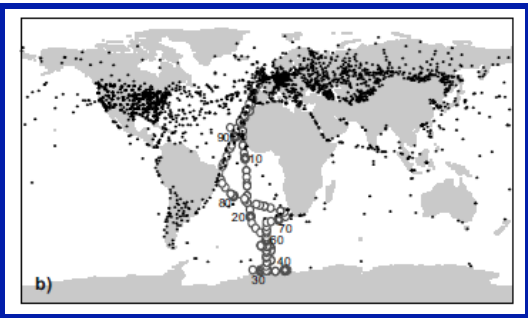




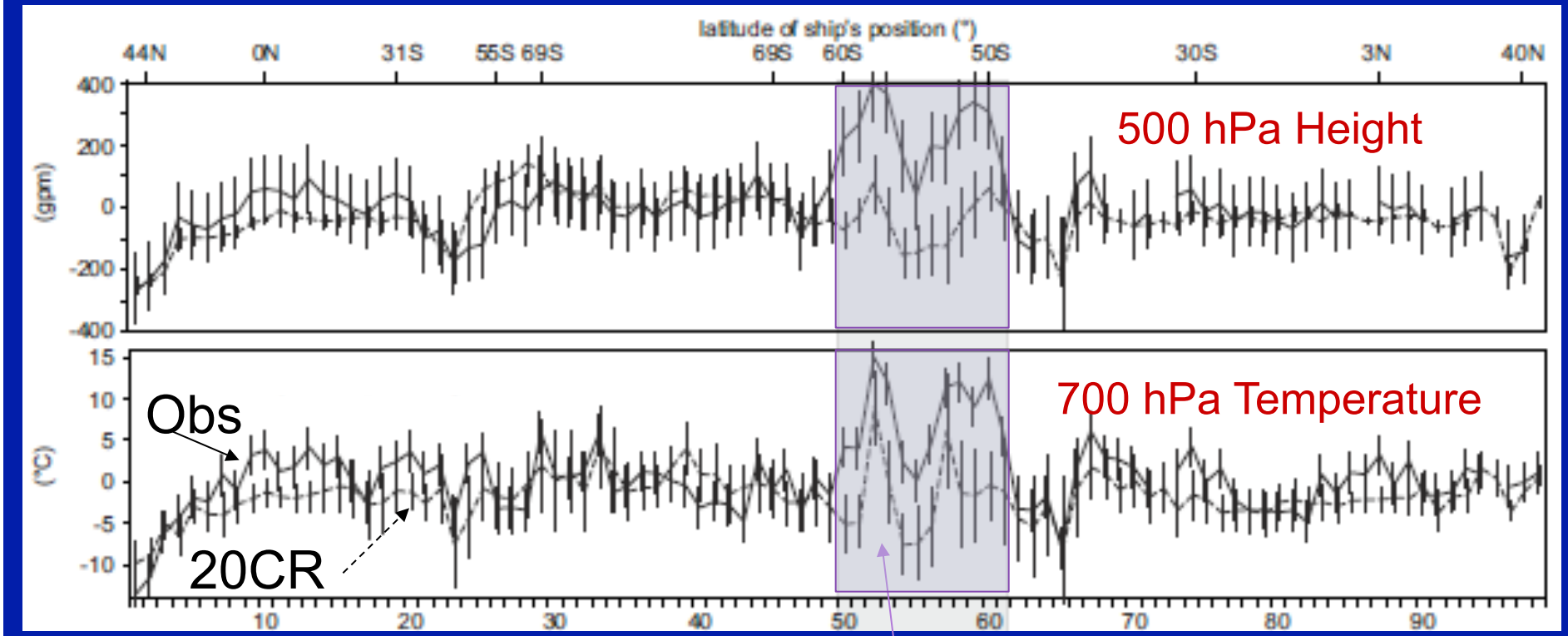
De Bruin and van den Dool (2010)

Upper-air anomaly data from cruise of MS *Schwabenland* compared to 20CR

(December 1938 to April 1939)



Cruise locations (open circles)



Anomalies are with respect to NCEP-NCAR Reanalyses

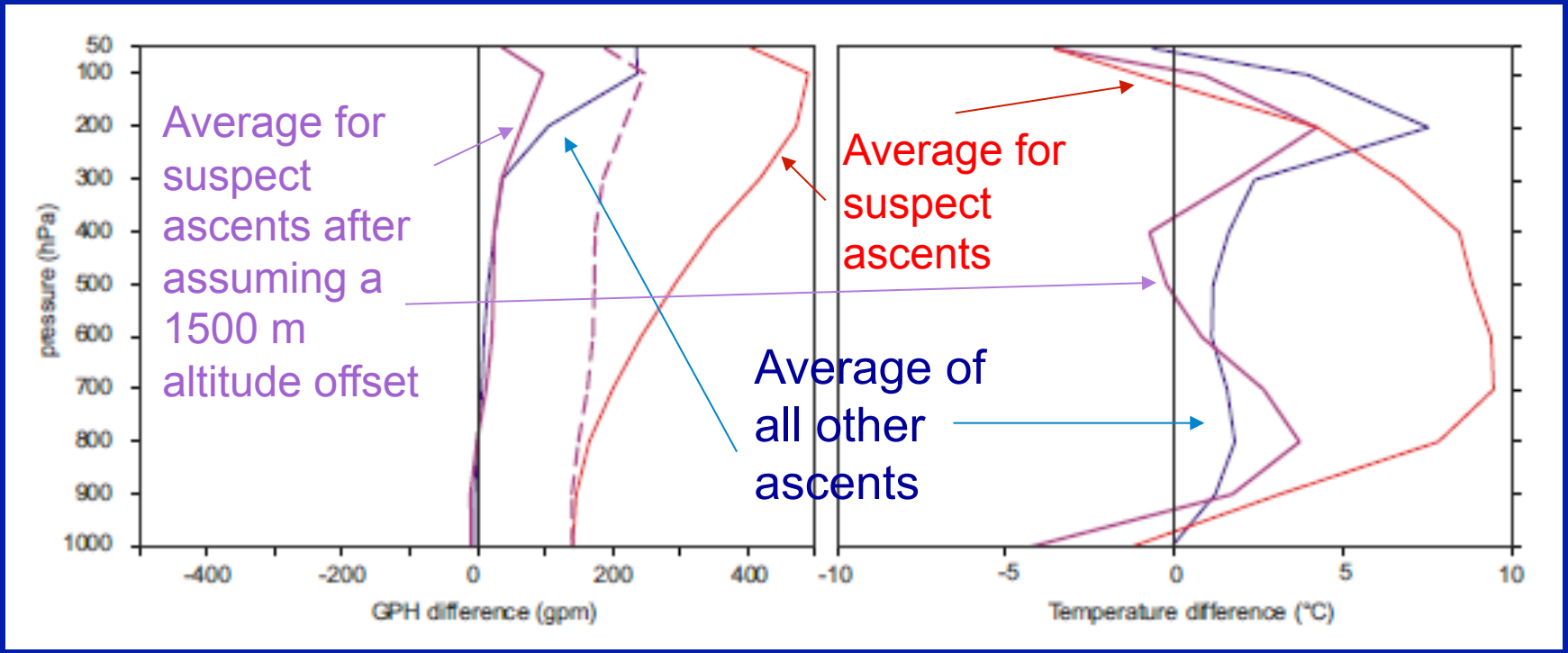
Grey regions shows suspected erroneous data

Brönnimann et al., Clim. Past (2011)

Vertical difference profiles of 20CR and MS Schwabenland geopotential height and temperature soundings

Geopotential Height

Temperature



20CR can be used to detect and correct errors in observations

Brönnimann et al., Clim. Past (2011)

Challenges to meeting National and International goals for Historical Reanalyses

- Satellite network only back to 1970's,
  Upper-air network comprehensive only back to 1940's, scant to non-existent in 19th century

- 3-D Var data assimilation systems such as used in NCEP-NCAR, NCEP-DOE, ERA-40 reanalyses depends on upper-air data for high quality upper-level fields (*Bengtsson et al.* 2004, *Kanamitsu and Hwang* 2005).

- However, studies using advanced data assimilation methods (e.g., 4D-Var, Ensemble Filter) suggest surface network, especially surface pressure observations, could be used to generate high-quality upper-air fields (*Bengtsson* 1980, *Thepaut and Simmons* 2003, *Thepaut* 2006, *Whitaker et al*. 2003, 2004, 2009, *Anderson et al.* 2005, *Compo et al.* 2006).

- Surface Pressure observations are consistent and reliable throughout 20th Century and provide dynamical information about the full atmospheric column.

Ensemble Filter Algorithm

Whitaker and Hamill (2002)

$x_j^b = \langle x \rangle^b + x'^b_j$ = first guess jth ensemble member (j=1,…,64)

y^o = single observation with error variance R

First guess interpolated to observation location:
$\langle y \rangle^b = H \langle x \rangle^b$, $y'^b_j = H x'^b_j$

Form analysis ensemble $x_j^a = \langle x \rangle^a + x'^a_j$ from

$$\langle x \rangle^a = \langle x \rangle^b + K (y^o - \langle y \rangle^b)$$

$$x'^a_j = x'^b_j + K^M (-y'^b_j)$$ Note the different gain

$$K = \Sigma_j x'^b_j y'^b_j (\Sigma_j y'^b_j y'^b_j + R)^{-1}$$ Kalman Gain

$$K^M = (1 + \{R/(\Sigma_j y'^b_j y'^b_j + R)\}^{-1/2})^{-1} K$$ Modified Kalman Gain shrinks the ensemble

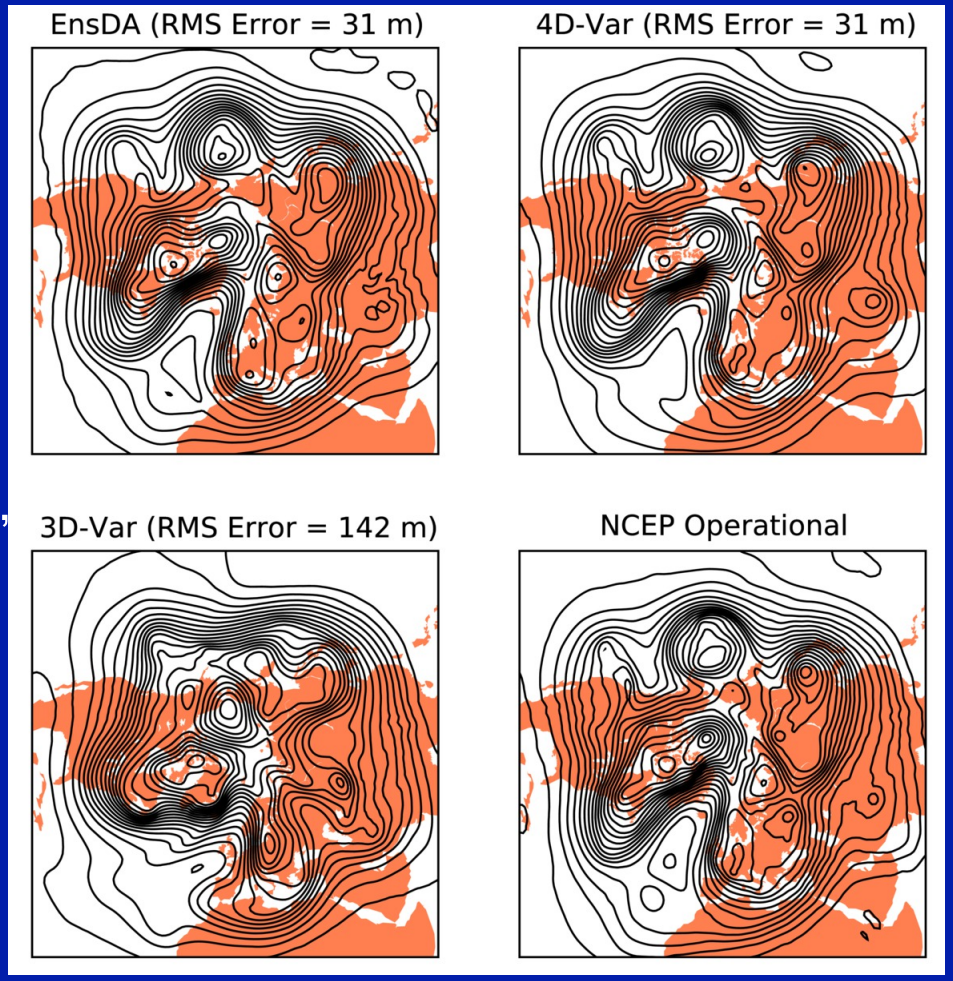
(1/(n-1)) is included in Σ_j

Analysis ensemble becomes first guess ensemble for next observation.

Conduct Observing System Experiments using only surface pressure (e.g., Whitaker et al. 2009).

500 hPA Height Analyses for 20 Feb 2005 12Z

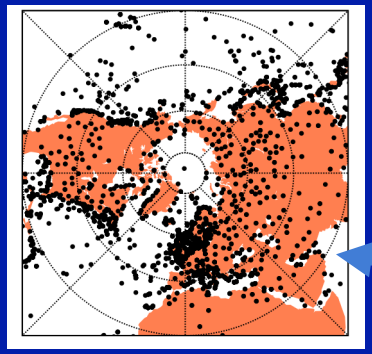
Ensemble Filter
(~3800 surface pressure obs)
RMS = 31 m



ECMWF "Surface" 4D-Var
(~3800 surface pressure obs)
RMS = 31 m

ECWMF "Surface" 3D-Var
(~3800 surface pressure obs)
RMS = 142 m

Full NCEP Operational
(1,000,000+ obs)

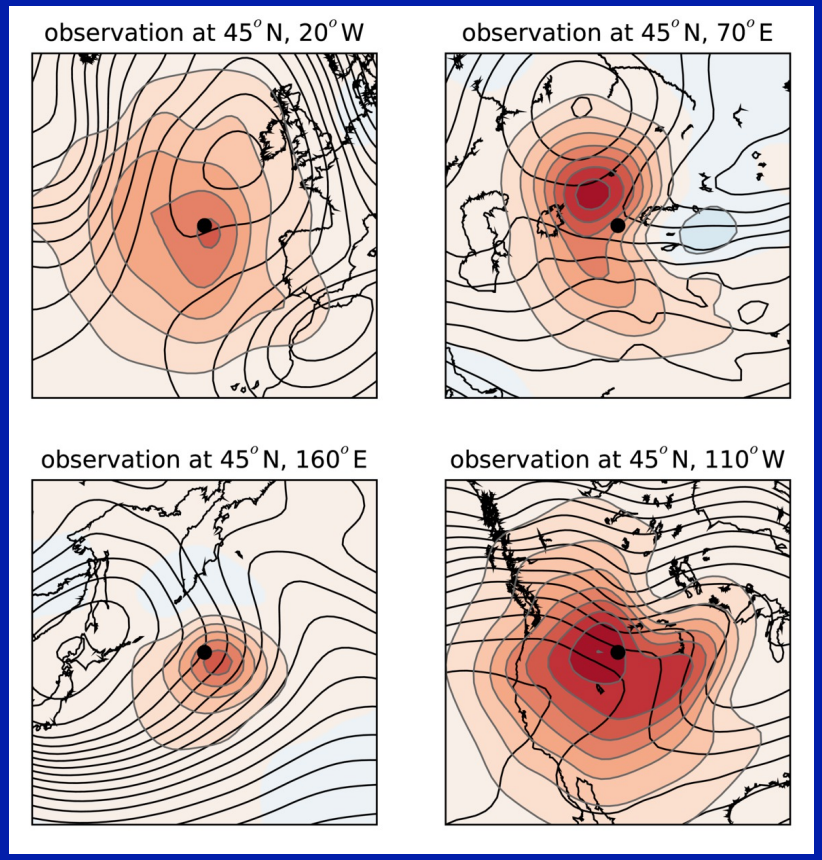


Surface pressure network reduced to ~1930's

Whitaker, Compo, Thepaut (2009)

500 hPa Geopotential height first guess (line contours) and analysis minus first guess (shaded) for single pressure observation 1 hPa greater than first guess at selected locations along 45N

Eastern Atlantic



Central Asia

West Pacific

North America

Ensemble Filter can extract spatially-varying structures relative to the flow and the previous observational density.

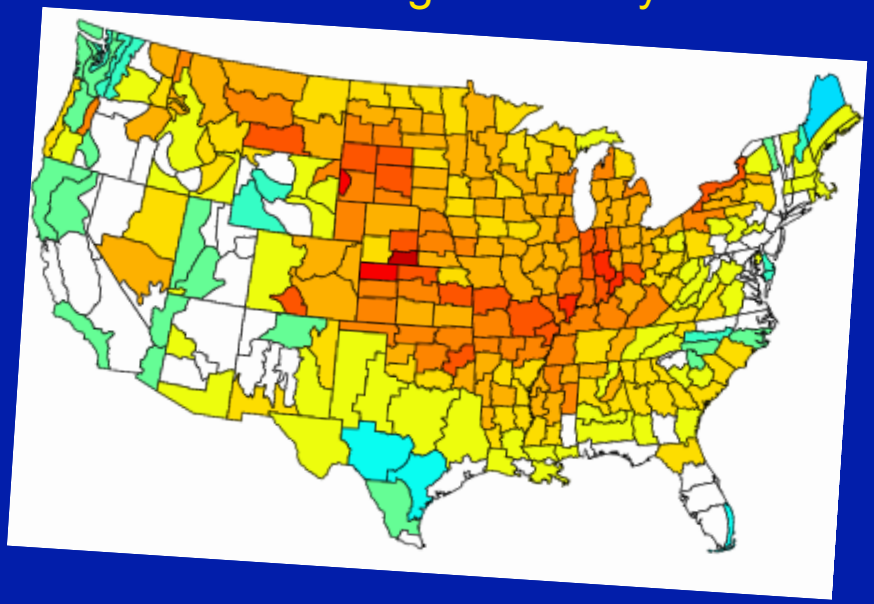
In the 3D-Var used in NCEP-NCAR Reanalyses, all of these structures would be identical and centered on the observation location.

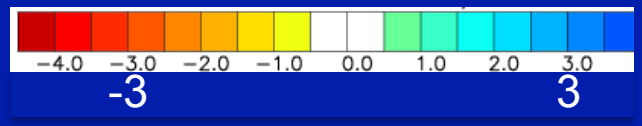
Whitaker, Compo, Thepaut (2009)

U.S Dust Bowl (July 1936)

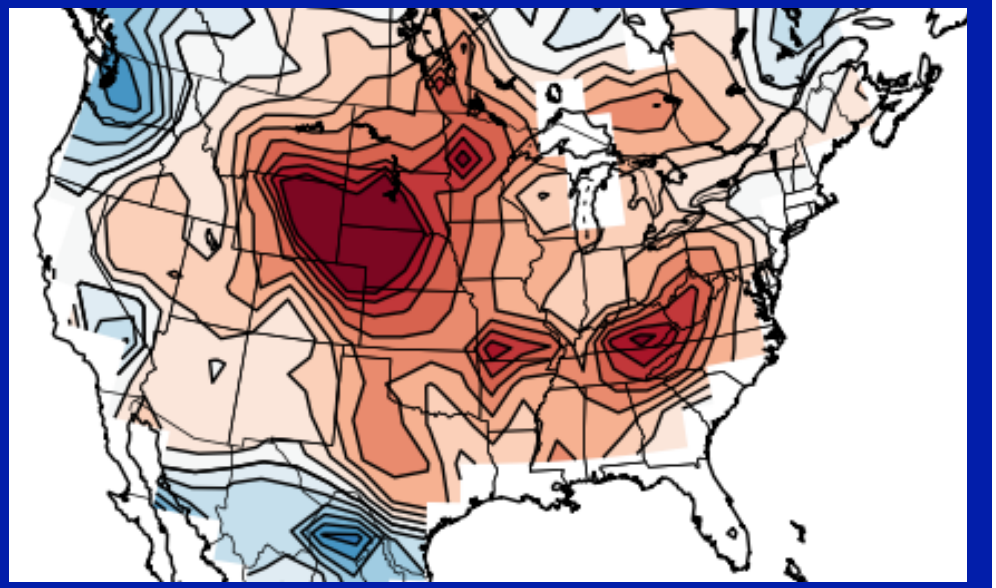
Standardized monthly anomalies relative to 1961-1990

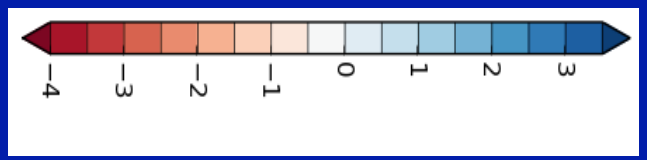
US Climate Division
Palmer Drought Severity Index





20CRv2 Soil Moisture 0-200 cm



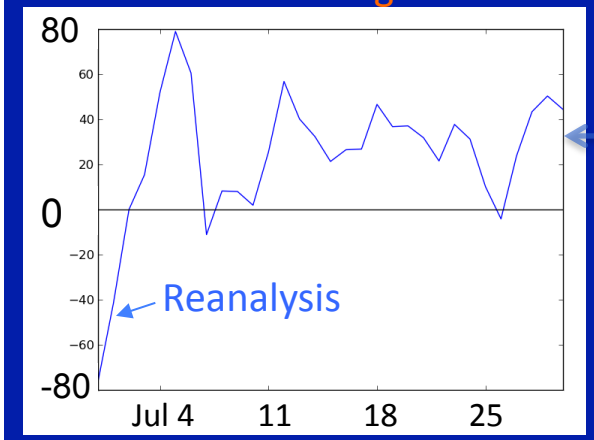


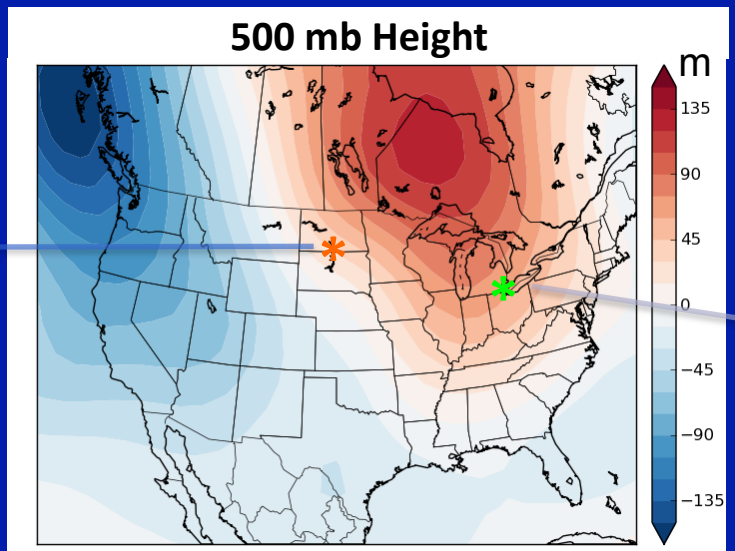
Using only surface pressure, 20CR v2 appears to capture expected features even in derived quantities.

July 1936 North American Heat Wave

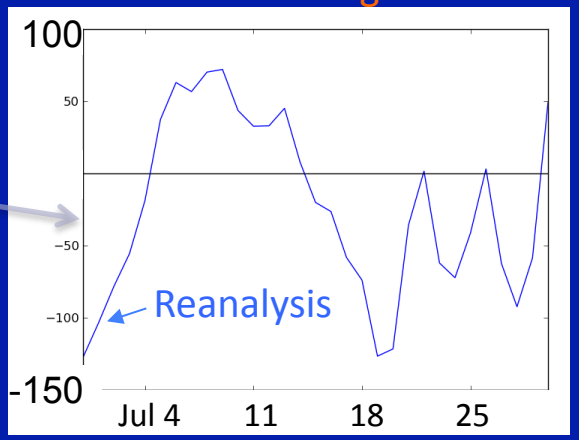
(1,000+ US & 1,000+ Canadian deaths during 14-day span)

500 mb Height

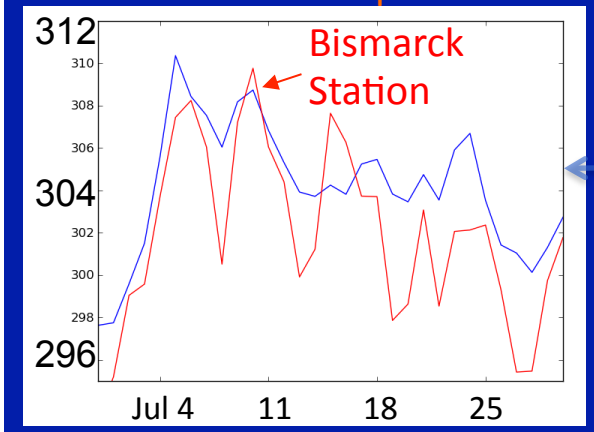


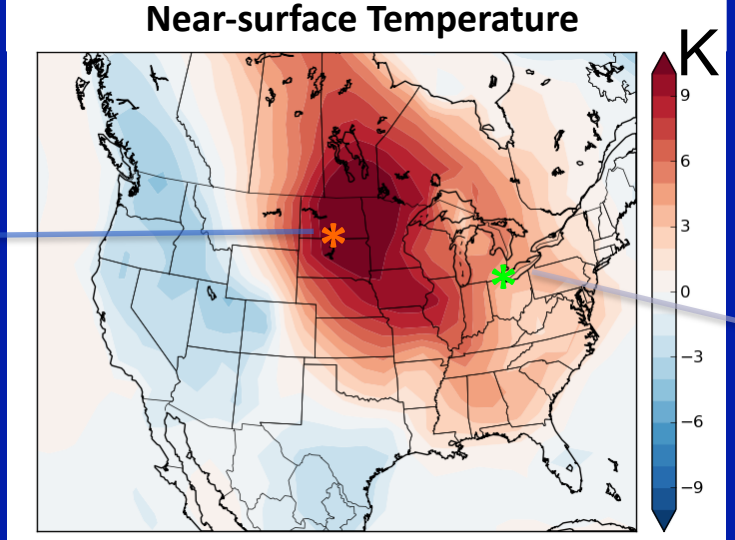


500 mb Height

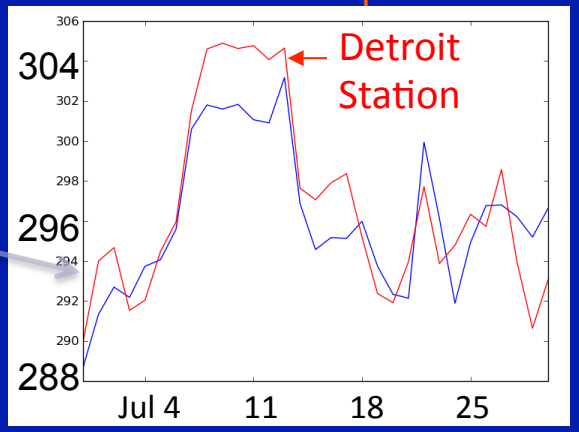


Near-surface Temperature





Near-surface Temperature

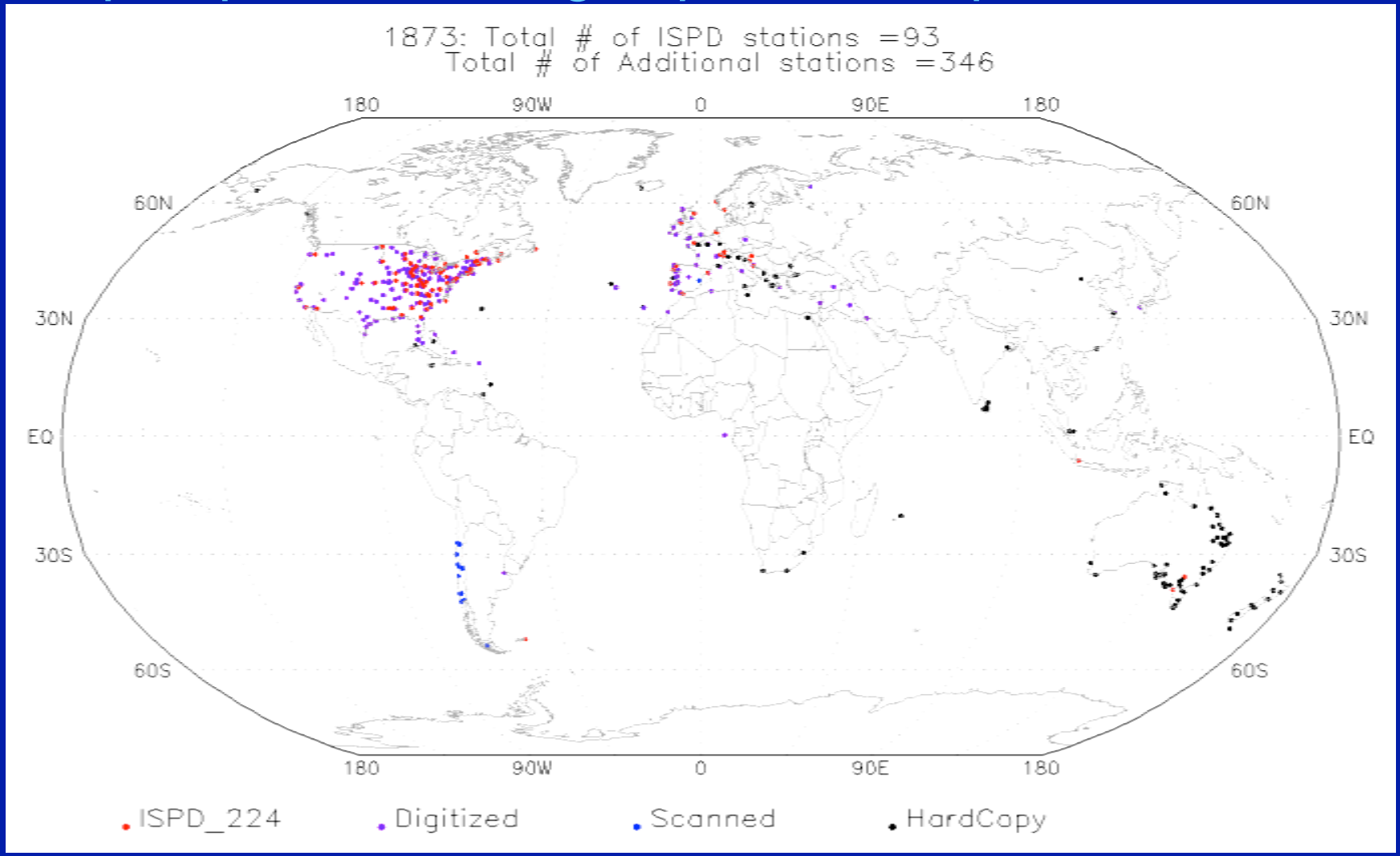


20th Century Reanalysis version 2

Anomalies July 8 – 14 with respect to 1891-2007

Current and future International Surface Pressure Databank station component (1670 to 2009)

ftp://ftp.ncdc.noaa.gov/pub/data/ispd/add-station

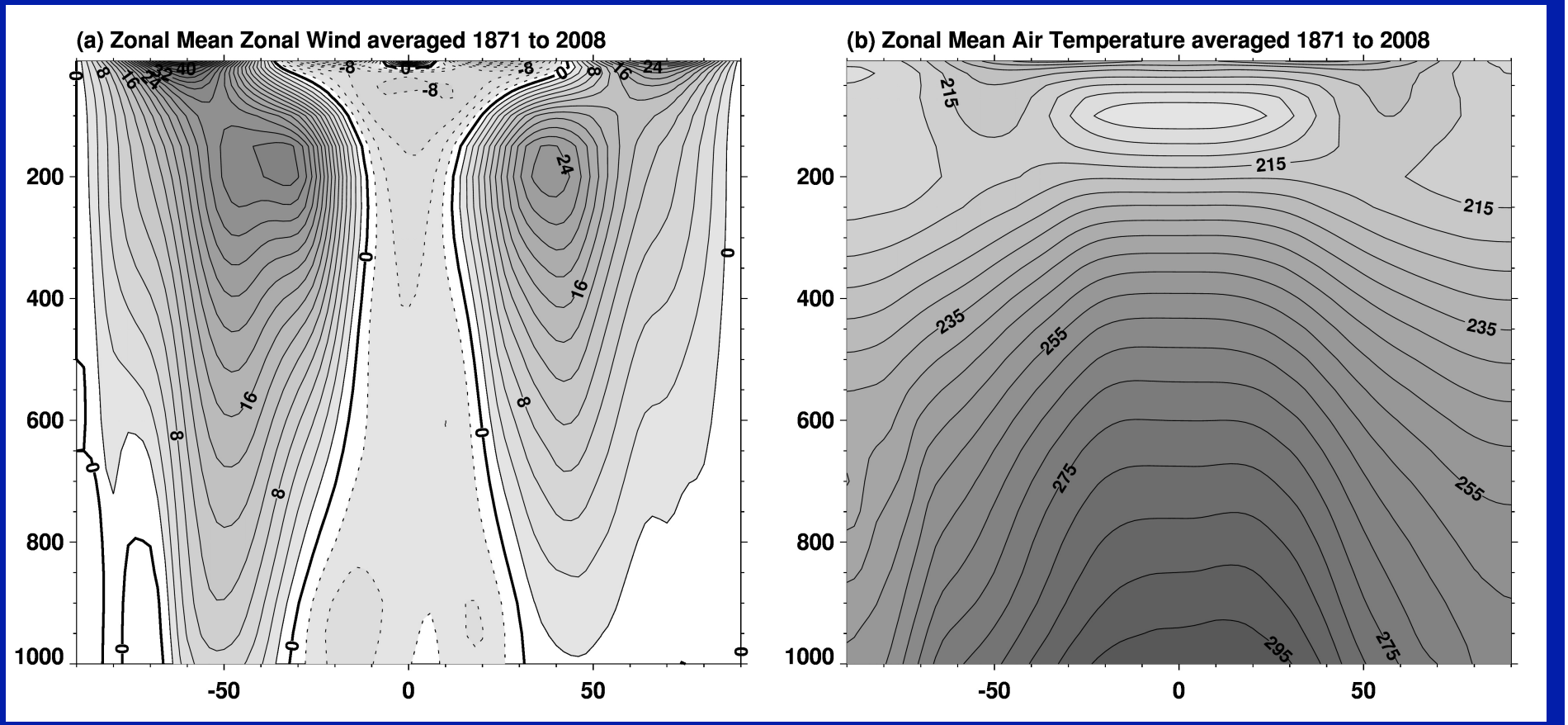


Courtesy X. Yin and R. Allan

1871 to 2008 Zonal Means

Zonal wind

Air Temperature



50S EQ 50N

50S EQ 50N

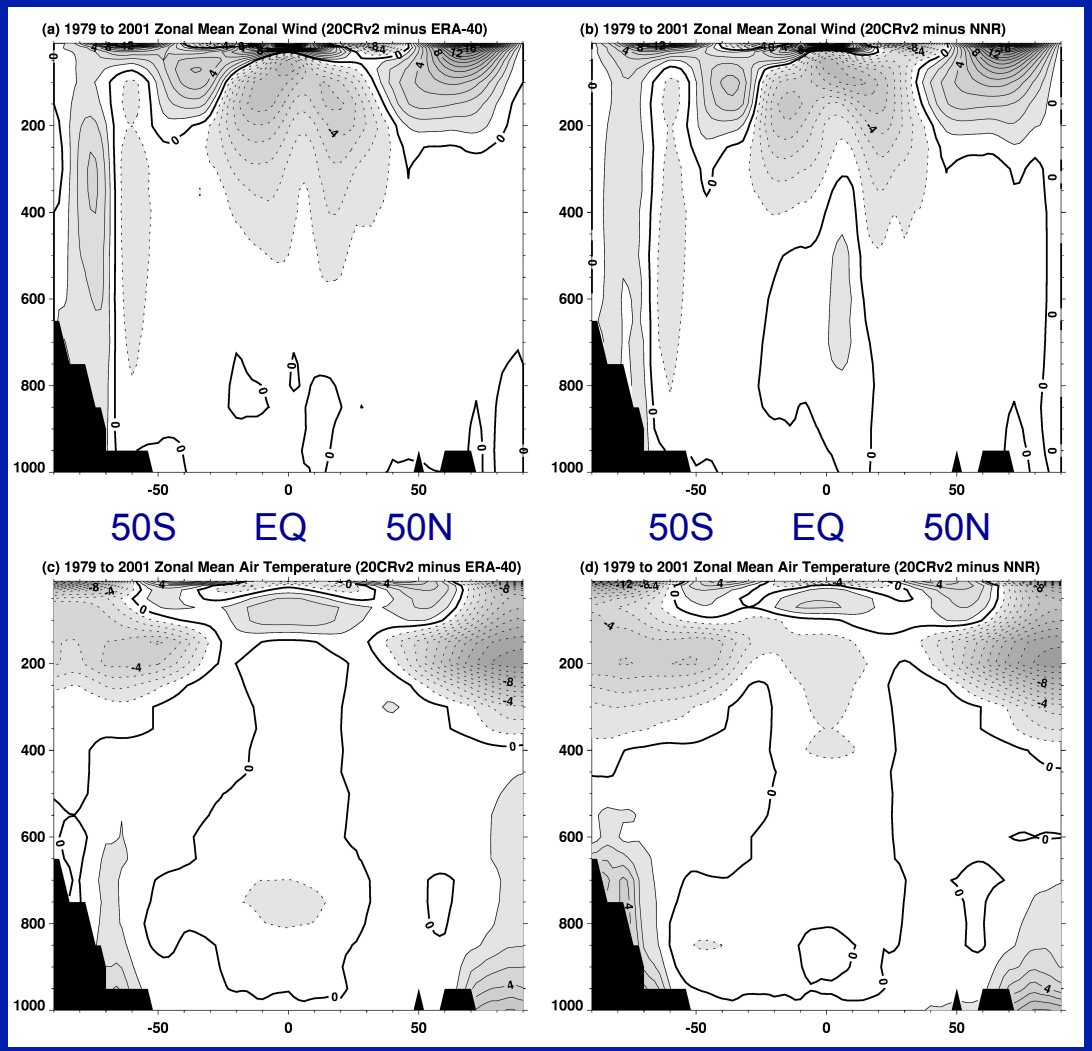
20CR zonal mean difference with ERA40 and NNR (1979-2008)

ERA 40 NNR

Zonal wind

200

1000



Air Temperature

200

1000

CI:1 m/s

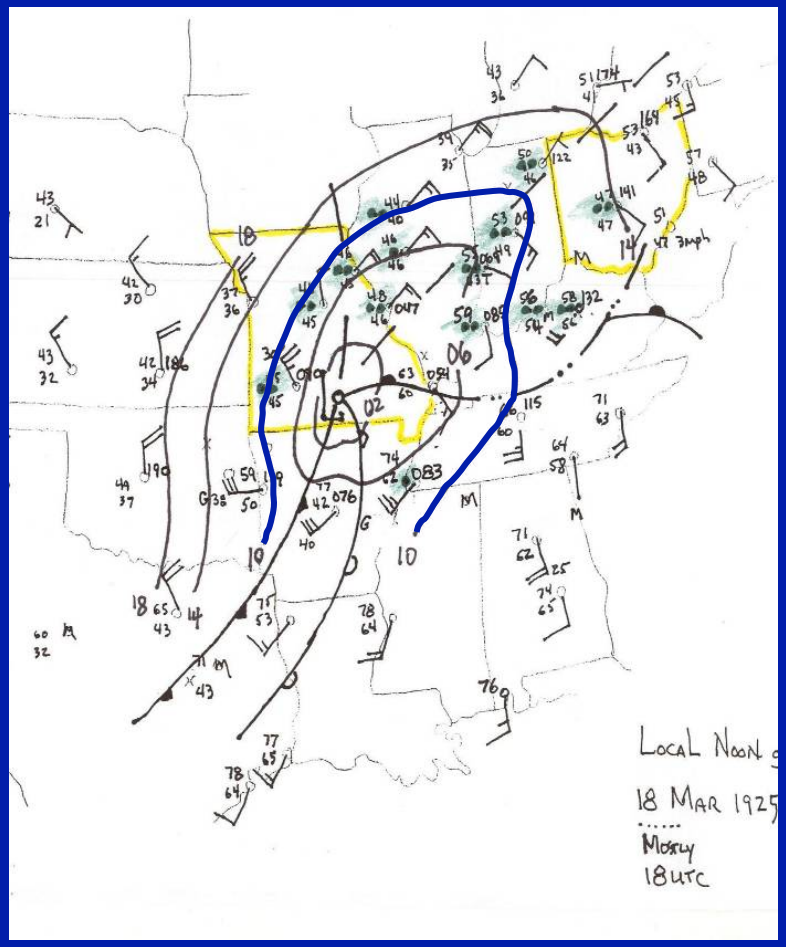
Biases Over Poles and Stratosphere

CI:1 K

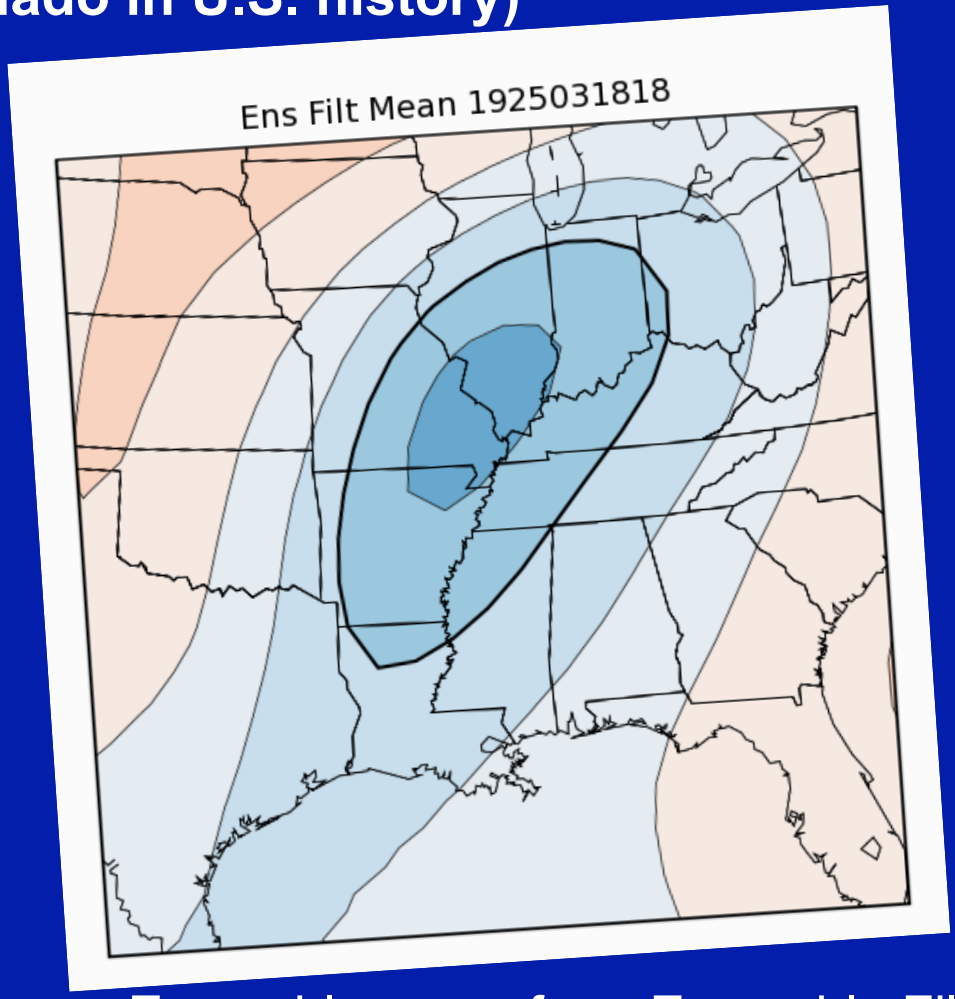
20CR biases are low and sometimes of opposite sign in most of troposphere.

Compo et al. QJRMS (2011)

Sea Level Pressure analyses for Tri-State Tornado Outbreak of 18 March 1925 (deadliest tornado in U.S. history)



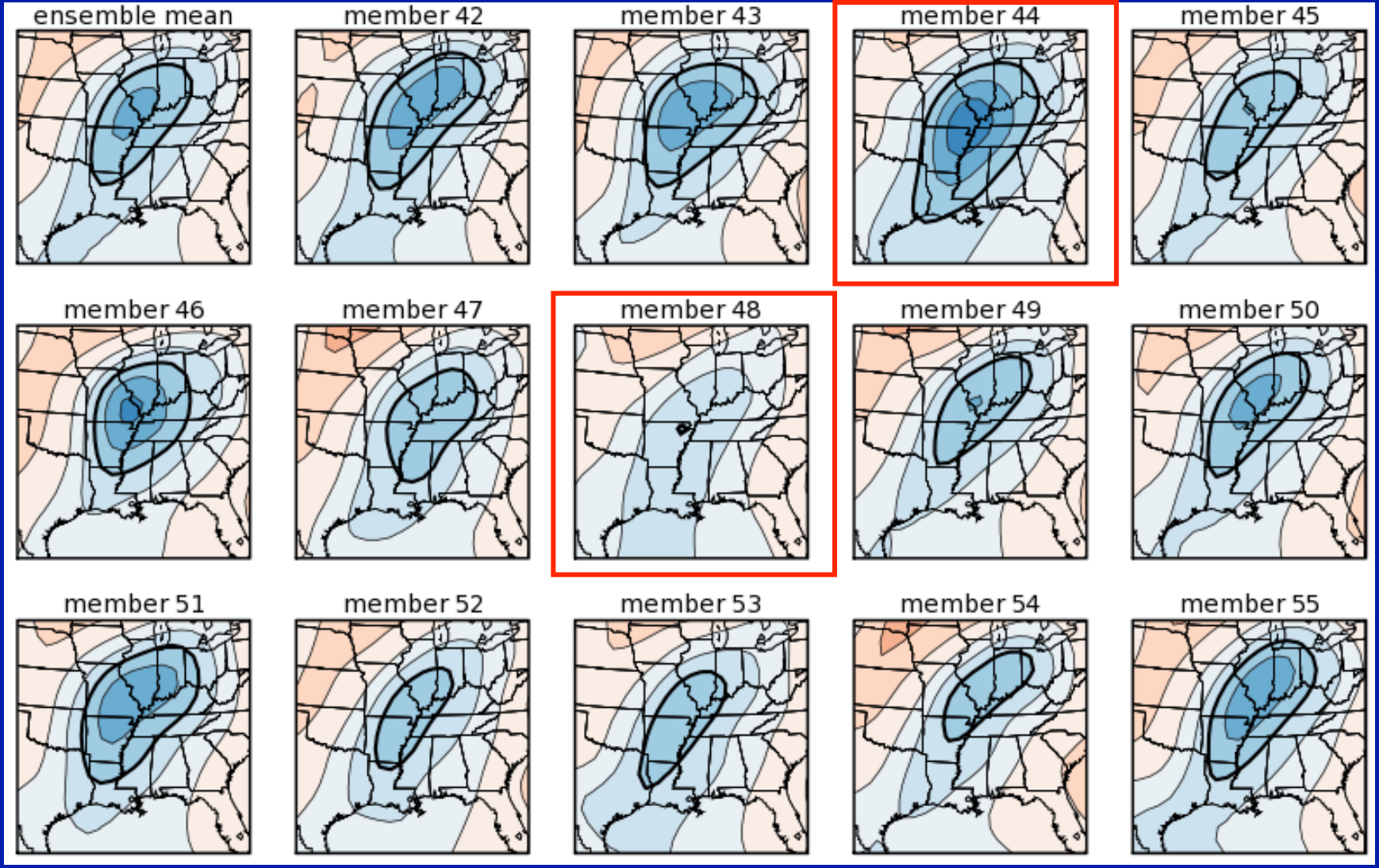
Manual Analysis, courtesy B. Maddox



Ensemble mean from Ensemble Filter
(4 hPa interval, 1010 hPa thick)

NOTE!!! This analysis did not use ANY of the observations shown on the left.

Range of possibilities for Sea Level Pressure
18 March 1925 18Z using 14 (of 56) members



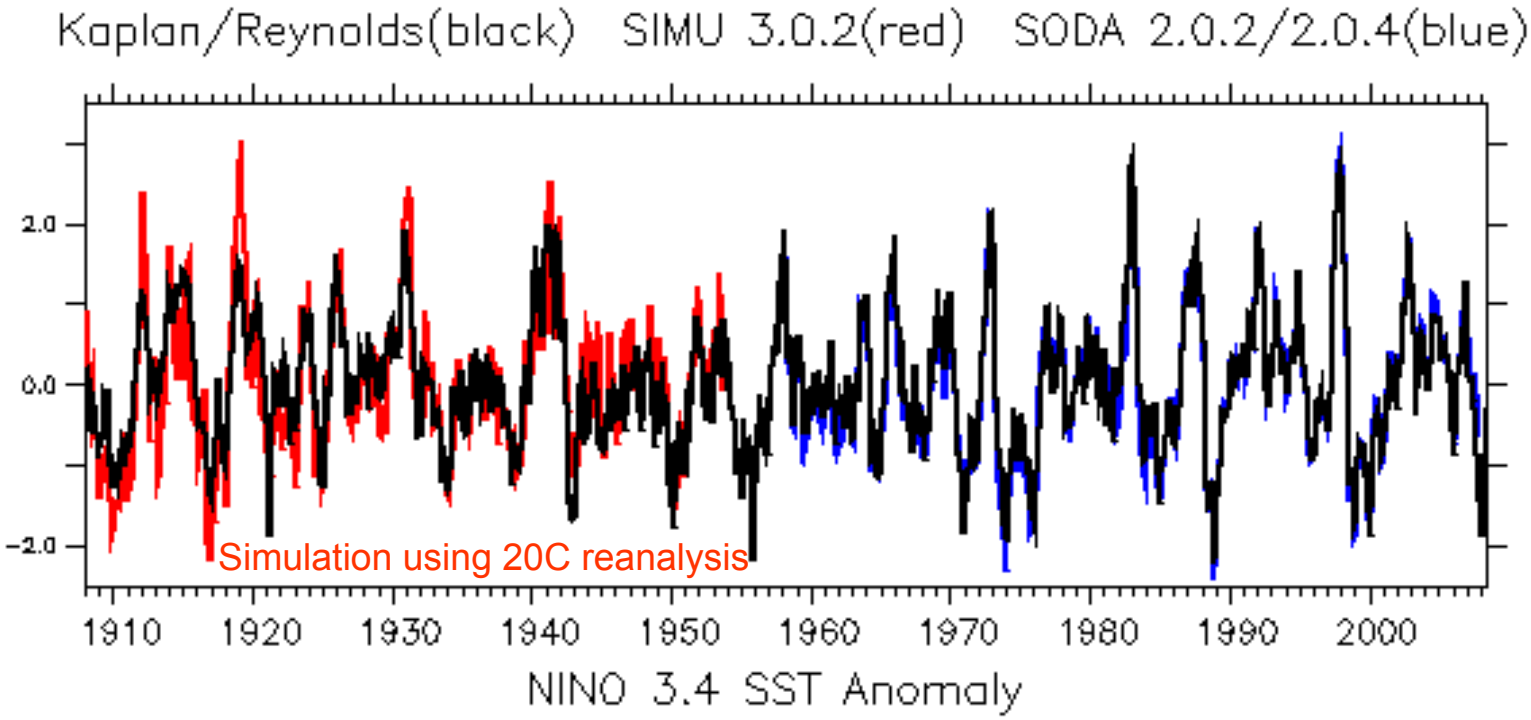
Ensemble of 56 possible realizations consistent with the observations

Tropical Validation

- Force global Parallel Ocean Program (POP) with daily 20th Century (1908-1956) reanalysis fields
  - 2m Air Temperature
  - 2m Specific Humidity
  - Downwelling Shortwave at Surface
  - Total cloud cover
  - 10 m Wind Speed
  - Precipitation
  - Zonal and Meridional Wind Stress

  (*Giese et al. BAMS 2009)*

Nino3.4 Time series from Kaplan SST, POP Simulation, SODA Data Assimilation



+20th Century reanalysis forcing fields with no adjustment generate realistic Nino3.4 variability in simulation

+Encouraging for Ocean and Coupled Data Assimilation.

(*Giese et al. BAMS 2009*)